MOVING STRIATIONS IN ARGON GLOW DISCHARGES

ORVILLE B. KARGE
AND
BENNETT W. HOOKS

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Orville B. Karge

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Bennett W. Hooks

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Thesis

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This work is accepted as fulfilling
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MASTER OF SCIENCE
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PREFACE

When a potential is applied between two electrodes in a tube containing gas, only a minute current flows until a certain minimum value of potential is reached. This minimum value is known as the sparking potential and at this point the insulating power of the gas is overcome, and the subsequent transport of electricity is accompanied by a characteristic emission of radiation which often has a beautiful appearance. Originally a matter of curiosity, this gaseous conduction is now of much importance both as a field of research in electro-magnetic and atomic phenomena and also in many technical applications.

Under many conditions there are, in the discharge, both standing and moving striations as evidenced by time and position variations in light intensity. No completely satisfactory theory has been generally accepted to explain them. The work described in this thesis was done at the United States Naval Postgraduate School in the later half of the academic year 1955 and is concerned primarily with the moving striation phenomenum. In this, the first phase of a long term project, experimental verification of existing information has been undertaken with special emphasis on correlation with the most recent theories which have been advanced.

The writers wish to express their sincere appreciation to Professor N. L. Oleson for his supervision, guidance, and help

throughout the project; to Professor S. H. Kalmbach for his co-operation in developing a suitable high vacuum system; and to Mr. John S. Chitwood, Jr. for advice and assistance in electronics matters.

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CHAPTER I

INTRODUCTION

1. Summary

This work is an experimental investigation of the most recently reported results of moving striation studies. Particular emphasis has been placed on the work of Donahue and Dieke which has recently been carried out at John Hopkins University. Argon gas was selected for this investigation and as a consequence the Donahue and Dieke reports involving this medium[4,5,6] are of primary interest. The experimental techniques and arrangements set forth in these reports have been duplicated to a close degree, and most of the observations therein have been re-examined.

Oscillations occur almost universally in glow discharges. They are almost always present within a large range of pressures and currents whenever a positive column exists. So seldom are they absent that it seems likely that any theory of gaseous discharge which neglects them is defective in an essential way. The study of these oscillations is a long term project, and much remains to be done. However, Donahue and Dieke have developed a tentative qualitative theory based on their observations. This theory is summarized in section 4. A primary objective of this work has been the testing of this theory.

2. Characteristics of the Glow Discharge

A short and at the same time adequate definition of a glow discharge is difficult to formulate. It is usually defined as a discharge with a relatively small current density, (.1 amp/cm^2), and a cathode fall of 50 volts or more, where the electrons are liberated from the cathode mainly by positive ions. The discharge has certain characteristic structural features which are described below.

When the gas pressure in the tube has been reduced to a few centimeters of mercury, an applied d.c. voltage produces a uniform glow throughout the tube. As the pressure is reduced still further (to a few mm) the glow is seen to be made up of alternate dark and light regions. Just in front of the cathode is a very short dark space called the Aston dark space. Following this is a region called the cathode glow whose length depends on the gas and pressure, next the cathode dark space or Crookes dark space, and then the brightest of the glowing regions called the negative glow. Following this there is a Faraday dark space and then a long glowing region called the positive column. At the anode there may or may not be (depending on gas and current value) an anode glow and an anode dark space. The above characteristics are depicted in Fig. 1 below.

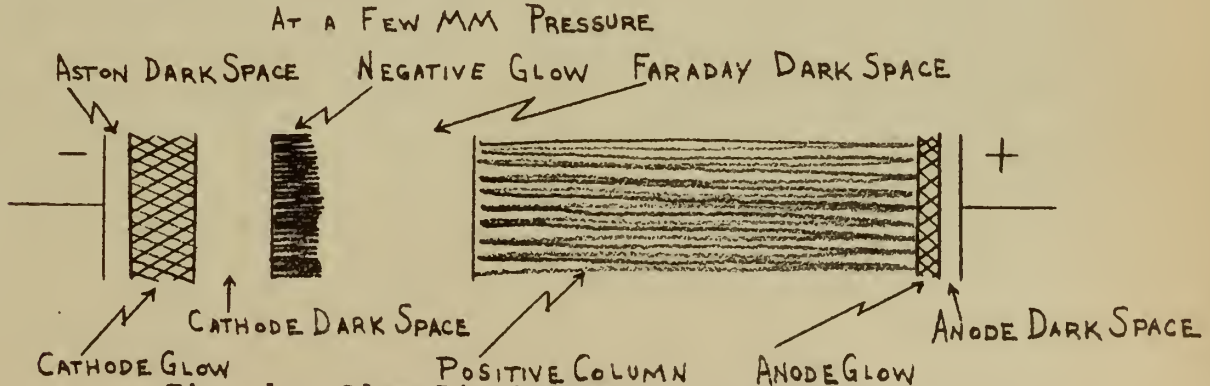


Fig. 1: Glow Discharge Characteristics

The negative glow and the positive column are typical examples of a plasma; that is, a region containing approximately an equal number of positive ions and electrons.

As the pressure is lowered all regions expand at the expense of the positive column until it completely disappears. The regions near the cathode are essential for the glow discharge. The positive column is not, but it is essential for the existence of striations.

3. A Brief History of Oscillatory Phenomena Investigations

Moving striations in rare gas and mercury glow discharges were discovered by Abria in 1843. A summary of the information which has been obtained since then can be found in any of the standard works on gaseous discharges such as those of Loeb[12] and Cobine[3] but this information has been fragmentary, and the oscillations have been one of the least understood phases of gaseous conduction. Prior to the work of Donahue and Dieke, probably the most extensive study of the oscillations was made by Pupp[13] who used a photo-cell and a cathode-ray tube to get a record of the light intensity fluctuations caused by the striations. Also of significance were the studies of electrical oscillations accompanying the moving striation which were made by Appleton and West[1] and by Fox[11].

Until recently, because of the difficulty of obtaining reliable and necessary data with the instruments which were available, no satisfactory explanation of the striations had been advanced. Dieke and Donahue, however, have apparently made real

progress with the applications of photo-tubes and the oscillograph in studying d.c. glow discharges driven by constant batteries. Such a discharge is probably the simplest and most easily evaluated one to investigate. The work described in this thesis employs the above technique along with a number of modifications and improvements which are described in Chapter II.

4. The Present Theory Explaining Moving Striations

a. Classical Theory of Gaseous Conduction

In terms of the accepted mechanism of gaseous conduction the current at the electrodes suffer fluctations in time of a statistical nature only. If γ is the number of electrons emitted per positive ion, then each of the electrons produced per positive ion striking the cathode must produce $\frac{1}{\gamma}$ ion pairs in the fall space in order that the discharge be self-sustaining. After passing out of the region of high field strength in the cathode fall and after losing energy in the negative glow, the primary and secondary electrons then travel into the positive column. Since the number of electrons passing any surface in the positive column per unit time is essentially constant, there is a steady current at the anode and at the cathode.

b. Defect in Classical Theory

It would seem that the above theory is defective in one important aspect. There is a difficulty concerning the process whereby the electrons can pass into the uniform field region of the positive column after having passed out of the region of large positive space charge in the fall space and after having

lost a considerable part of their energy by excitation of neutral atoms in the negative glow. Space charge distribution is such that there would be a minimum of potential near the Faraday dark space, and a trap would exist for the electrons in the negative glow around the corresponding potential maximum. If these excess electrons in the negative glow are not removed then the current delivered to the positive column would not be steady but would decrease as the negative space charge in the negative glow increased and spread toward the cathode. The field in the Crooke's dark space would decline causing the positive ion current to the cathode to diminish, and the discharge would be extinguished due to the critical nature of the cathode fall.

c. Donahue and Dieke Theory on Role of Positive Striations

Positive striations are considered to be regions of high positive space charge which travel toward the negative glow. They arrest the negative glow electron entrapment process before it has proceeded too far. When a positive striation gets sufficiently close to the trapped electrons, the barrier is lowered, and electrons will be released in a burst at the anode edge of the negative glow to travel toward the positive striation. Such a burst is a negative striation. When the electrons leave there is left behind a positive space charge which starts traveling through the negative glow toward the cathode. This raises the cathode fall causing greater emission at the cathode in the form of a negative striation which meets the oncoming positive striation at the cathode edge of the negative glow. A neutralization

process results and the electron entrapment process begins anew because the positive striation in the positive column has been neutralized by this time by the negative striation which it drew out of the anode edge of the negative glow. Here again occurs an electron entrapment process followed by a neutralization process. The negative striation feeds so much charge into the positive striation that a plasma of low total charge density is formed. Both striations stop; excitation of neutral atoms and light emission decrease. The positive striation can no longer move forward and draw electrons out of the negative glow until a second positive striation draws close from behind to release the electrons entrapped in the first positive striation. The cycle is repeated until eventually the first positive striation becomes free so close to the negative glow that it travels all the way to the cathode edge of the glow where it is met by a negative striation from the cathode.

The above description means that, in the positive column, electron bunches travel from one positive striation to the next toward the anode. Each positive striation periodically releases these electron bunches from the positive striation ahead as it travels toward the cathode between entrapments.

d. The Origin of the Positive Striations

The positive striations arise near the anode. The reason behind this is not too clear, but they always leave the anode at a time when the voltage across the discharge tube is a maximum. Apparently, after one positive striation draws away from the a-

node, the electrons traveling between this striation and the anode arrive near the anode with ever increasing energy until they have built up a large cloud of positive ions by collisions with neutral atoms in front of the anode. This shields the anode, and the current drops until the positive ion space charge has built up enough to be moved away from the anode by the mechanism of positive striation movement which is described in the next paragraph. It thus becomes a positive striation and starts out for the cathode until it stops a negative striation near the anode. This negative space charge finally is released to the anode when the anode reaches a potential high enough to draw it away

e. The Mechanism of Positive Striation Movement

There must be a reason why the positive striations move. It is thought that this movement; that is, the shift in positive ion concentration toward the cathode, is caused by the manner in which ionization occurs near the striation. In other words there must be a distribution of ions and excited atoms such that the configuration tends to preserve itself by moving toward the cathode. To explain the reason for such a distribution consider three points in order X_1, $X - \Delta X$, and X with X_1 nearest to the cathode., Let there be a positive space charge peak at X. It is believed that the electrons arriving at X_1 have the peak of their energy distributions just above the energy levels of the metastable states. Here the rate of production of metastables will be highest but at $X - \Delta X$, because of the known striation movement, the concentration of the metastables will be the highest. The

electrons arriving at X_1 produce metastables, losing energy in the process but gaining energy again on the anode side of X_1. At $X - \Delta X$ where the metastable population is high, the electrons produce highly excited atoms and ions, again losing energy. At X little ionization will take place because of the low concentration of metastables and due to the electron energy losses at $X - \Delta X$. Thus at X no new ions are being produced and the ion concentration falls due to various factors which cause ion loss such as lateral motion to the walls. On the anode side of X the electrons, which could not produce many excited atoms even at X because of their low energy, will continue to lose energy in a negative field and will, therefore, no longer contribute any excitation.

The mechanism described above will cause the highest concentration of metastables followed by the highest concentration of ions to shift toward the cathode with time and would, therefore, explain the motion of the positive striations toward the cathode.

In this connection, it has been shown by Watanabe and Oleson[16] that if it is assumed that the concentration of positive ions and electrons change by small amounts, the continuity equations applicable to the positive column yield a solution predicting density waves traveling from the direction of the anode towards the cathode. These waves consist of a periodic fluctation of positive ion density leading a corresponding fluctuation of electron density, both of approximately the same amplitude.

CHAPTER II

APPARATUS AND EXPERIMENTAL TECHNIQUES

1. Old and New Methods

A prime reason for the present lack of detailed information and a well tested theory of electrical conduction in gases is the difficulty in obtaining accurate data with available instrumentation. Previous studies have employed rotating mirrors and cameras[2], photoelectric cells[13], and more recently the photomultiplier tube and oscillograph[4,5,6] to measure oscillations in light intensity of the discharge. The devices and techniques used in this study were closely patterned after those employed by Donahue and Dieke[4,5,6] in their recent work at the Johns Hopkins University. Among the added innovations, which have not yet been reported in the literature available to the writers, are:

a. Frequency measurements with an electronic counter which permits essentially continuous and instantaneous frequency monitoring.

b. Adaptation of probe techniques similar to those used by Pupp[13] to provide for simultaneous viewing of discharge light intensity oscillations and probe voltage oscillations with a dual beam oscillograph.

c. Using a constant voltage transformer to supply power to all electrical units and a long warm-up period to ensure stable operating conditions.

Fig. 2 - 6 are photographs of the experimental layout used and depict actual operating conditions and arrangements of the equipment. Diagrams of the various circuit arrangements, vacuum and gas filling systems, and discharge tube details are contained in Fig. 7 - 12, and further described in the following paragraphs.

2. Specifications of the Discharge Tube and Degassing

The discharge tube was fabricated by I. C. Dumas of Stanford Research Institute to design specifications by Professor N. L. Oleson of the U. S. Naval Postgraduate School. This tube was of pyrex glass with tungsten wire probes and pure zirconium (essentially hafnium free) electrodes. The de-gassing of the tube walls, probes, and electrodes was considered to be most essential to achieve and maintain a high degree of purity of the discharge gas. This was accomplished, under high vacuum, by the repeated techniques of:

a. Heating electrodes to a cherry red with a Scientific Electric Co. Model AC-5-LB Induction Heating Generator.

b. Heating entire tube to about 500°C for several hours with electrical heating tapes and asbestos paper lagging.

c. Flaming with a soft flame from a gas torch.

d. High current positive ion bombardment of the probes and electrodes to white heat by the neon sign manufacturing technique utilizing approximately 1200 volts across the tube from a transformer, and a leak detector to initiate discharges in a few millimeters of argon. A word of caution concerning the use of this last method is in order, since it can lead to dis-

asterous results. In this instance, for a small diameter tube with fine probes, it resulted in an undesirable but non-disenabling deposit of zirconium metal on the tube walls at the electrodes and the complete disappearance of probes #3 and #4 (upper).

3. High Vacuum and Gas Filling Systems

The discharge tube was mounted horizontally on a portable rack and table with supports for blackout curtains, optical system, and all the accessory vacuum and gas filling systems and devices. This arrangement was also designed by Professor Oleson and glass work was done by I. C. Dumas with all repairs and modifications of the glass work done at the U. S. Naval Postgraduate School by Professor S. H. Kalmbach. As is usually the case, these modifications, repairs, and the correction of leaks were very time consuming but ultimately resulted in the achieving of a high vacuum in the order of 10^{-8} mm Hg., as indicated by a Consolidated Vacuum Co. Type DPA-38 Ionization Gauge. Such a high vacuum is highly desirable in order to ensure the freedom of the system from impurities. It was obtained with the following equipment:

a. Duo-Seal Vacuum Pump as forepump

b. A three-stage air cooled Consolidated Vacuum Corp. Type GF-25A 75v Diffusion pump using Octoil-S Vacuum Pump Fluid

c. Two liquid air traps-one at the suction side of the diffusion pump and the other between the manometer and discharge tube inlet stopcock. Type N Apiezon Grease was used on all stopcocks.

This investigation was confined to discharges in Argon gas at 12 millimeters pressure since a monatomic gas at this pressure appears to afford simple conditions for study of gaseous conduction. A one liter pyrex glass flask of Linde high purity argon gas at about one atmosphere pressure was sealed onto the system, and filling was accomplished by means of a pair of stopcocks on either side of a small bulb reservoir. The gas pressures in the tubes were measured with a 100 cm. Octoil - S manometer (1 cm = 0.672 mm Hg) after which the tube was isolated by means of its stopcock and the entire remainder of the system again pumped down to a high vacuum. All glass tube walls and the manometer fluid were repeatedly flamed, under high vacuum, with a soft torch. Thus, these arrangements provided for a high degree of purity of the gas in the discharge tube and facilitated the filling of the discharge tube with argon and maintenance at any desired pressures up to about one atmosphere. It will also be noted that this experimental layout provides for complete flexibility in future replacement of various designs of discharge tubes and replacement with flasks filled with any desired gases at all pressures in the desired experimental range.

4. Power Supply to Instrumentation and Discharge Tube

Although some previous surveys have been made using an a.c. discharge to study break-down and transitory phenomenon[8], this study was restricted to the observation of discharge phenomena under the most stable and time independent conditions obtainable,

since such a study should lead to the most direct and easily evaluated results. Therefore a Sola Type CSY-301495 Constant Voltage Transformer was used to supply regulated 115v., 60 cycle a.c. power to all electrical units and, from this regulated power supply, a General Electric Type YPD-4 Regulated Power Supply was used to furnish d.c. power for the discharge tube. This unit is rated at 160 - 1500 volts and 0 - 125 m.a., with 0.15% or less regulation from no load to full load, and less than 0.05 volts peak to peak ripple and noise. Additionally, all electrical units were given a minimum of four hours warm-up period and the discharge tube was operated for the same minimum time, to establish stable operating conditions, before any data was recorded. Discharge tube voltage and currents were measured with a Weston Model 931 voltmeter (5000 ohms/volt) and milliammeter. These instruments were calibrated immediately before starting the tests and recorded readings were corrected where applicable. An adjustable current limiting resistor in the circuit to the cathode was fixed at 14,000 ohms for all work except where otherwise noted.

5. Optical System and Photomultiplier Tube

Essentially the technique of studying moving striations in the discharge consists of observing, recording, and analyzing the phenomena they exhibit. An analysis of the current variations with time and space for probes in the discharge can lead to a determination of the time and space variations of electron temperatures, space charge densities, and electric field intensities

as described in section 8. A more simple and perhaps more convenient method is that of investigating the time and space variations in the light intensity of the discharge by means of a photomultiplier tube and oscillograph. The light from any point in the discharge is focused, by means of a pair of mirrors mounted on a carriage and traveling on a rack and pinion, through a condensing lens and onto a slit in the photomultiplier tube housing. The optical system used in this work was designed by Professor Oleson and manufactured at the U. S. Naval Postgraduate School. A 1P-21 photomultiplier tube, with its associated power supply, was used to give optimum signal to noise ratio with an amplification of the order of 1×10^6.

6. Oscillograph Displays and Analysis

The output currents of the photomultiplier tube were impressed across a 100,000 ohm resistance at the Y input terminals of one channel of a DuMont Type 322-A Dual-Beam Cathode Ray Oscilloscope. The oscilloscope sweep was triggered externally by the voltage oscillations at the cathode through a 4 microfarad 1100 volt d.c. blocking condenser. Thus the pattern on the screen shows the variation in light output from any preselected point in the glow discharge with reference to the time of a voltage maximum at the cathode. It was of course first necessary to verify that discharge tube voltage oscillations were of the same period as the light intensity fluctuations. This was easily demonstrated both by the fact that successive oscilloscope light intensity traces always duplicated themselves exactly in phase for any given

point in the discharge, and that this phase relationship varied in a predictable manner as the optical carriage was moved along the tube. Additionally, a direct comparison of the time variations of the discharge tube voltage with fluctuations in light intensity was made by impressing these voltage variations across the Y input of the second oscilloscope channel as illustrated in Fig. 10. Similarly the tube voltage oscillations may be compared with the current oscillations at the anode and cathode by utilizing the circuits of Fig. 11 and 12. The results of the foregoing comparisons are discussed and analyzed in Chapter III.

The oscilloscope used for the above and all other measurements was completely checked and calibrated before any data was taken. A Browning Laboratories, Inc. Model GL-22A Sweep Calibrator was used to apply negative intensity modulation at 100 micro-second intervals to the Z inputs of both channels. By means of these marks the period, wavelength, and velocity of the moving striations were easily obtainable by moving the optical carriage a measured distance equal to one alternation or through a convenient time interval as indicated by the time marks.

As measurements were made and recorded for various currents, voltages, modes of oscillations, and points in the glow discharge, the oscilloscope patterns were photographed by means of a DuMont Type 295 Oscillograph Record Camera. Kodak Ortho-Linograph film with a lens setting of f/2.8 and an exposure time of one 1/25 sec. was found to give very satisfactory results. These films were later enlarged on a photoreader from which accurate measure-

ments could be determined and correlated with the data. To provide reference voltage levels and a calibrated voltage scale a double exposure technique was employed whereby the first exposure displayed the zero voltage levels (vertical amplifiers "off") and the calibrated voltage grid of a DuMont Type 2562 B Illuminated Scale; and the second exposure superimposed the oscillograph pattern under investigation. All pictures were obtained by this method.

7. Striation Frequency Measurements

It is essential that discharge conditions remain constant during a particular set of observations. This may be verified by frequent checks on the constancy of voltage and current and the steadiness of the discharge glow. A more convenient and highly sensitive device was to monitor the frequency of the oscillations with a Hewlett Packard Model 522 B Electronic Counter. This instrument gives frequency readings as often as once each .1 sec. with an accuracy of $\pm$ 1 count. All other work, published to this date and available to the writers, did not make use of this technique.

8. Probe Circuits and Techniques

As previously stated, an additional objective of this work was to develop and test a method of analysis of the discharge using probes. The technique used was proposed by Professor Oleson. Such methods, utilizing the dual-beam oscilloscope for measurement and analysis, also have not been reported in the recent literature available to the writers. A continuously variable voltage from

0 - 180 volts negative with respect to the anode was supplied from batteries and a potentiometer to the selected probe via a 20,000 ohm resistor. A.C. variations in voltage were bypassed with a 200 microfarad, 600v. condenser across the potentiometer section in use. Battery voltage and average d.c. probe current were measured with a recently calibrated Weston Model 622 voltmeter and milliammeter with reversing switch. The current through the resistor was impressed as a voltage drop to the input of one oscilloscope channel. Thus time and space variations of probe current could be photographed, measured, compared, and correlated with any other discharge parameter. The detailed analysis of this data is contained in Chapter IV. The future applications of this technique and the determinations of time and space variations of electron temperatures, space charge densities, and electric field intensities should contribute greatly to the complete understanding of gaseous conduction.

Key to Apparatus in Figures 2-6

A: Discharge tube

B: Optical carriage; rack and pinion

C: Condensing lens

D: Photomultiplier cell housing and slit

E: Vacuum forepump

F: Vacuum diffusion pump and cooling fan

G: Liquid air traps

H: Flask of argon

I: Filling stopcocks

J: Manometer

K: Ionization gauge

L: Blackout curtains

M: Constant voltage transformer

N: Regulated power supply

O: Current limiting resistors

P: Tube circuit voltmeter and milliammeter

Q: Dual-beam oscillograph

R: Sweep calibrator

S: Electronic counter

T: Probe supply batteries

U: Probe supply potentiometer

V: Probe circuit bypass condensers

W: Probe voltmeter, milliammeter, and reversing switch

X: Leak detector

Key to Apparatus in Figures Cont.

Y: Photomultiplier cell supply unit

Z: Photoreader

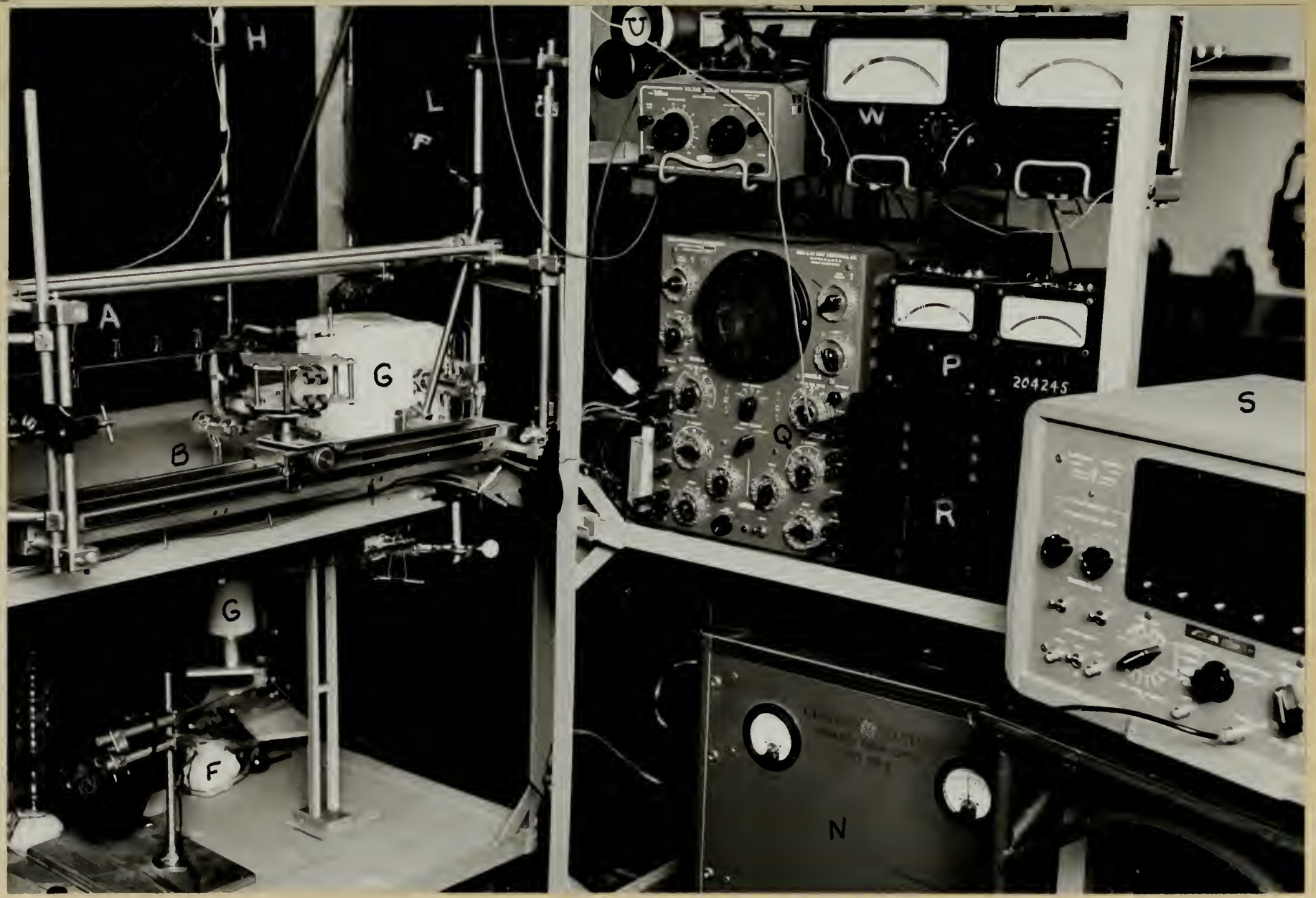


Fig. 2: Experimental Apparatus From Operator's Position

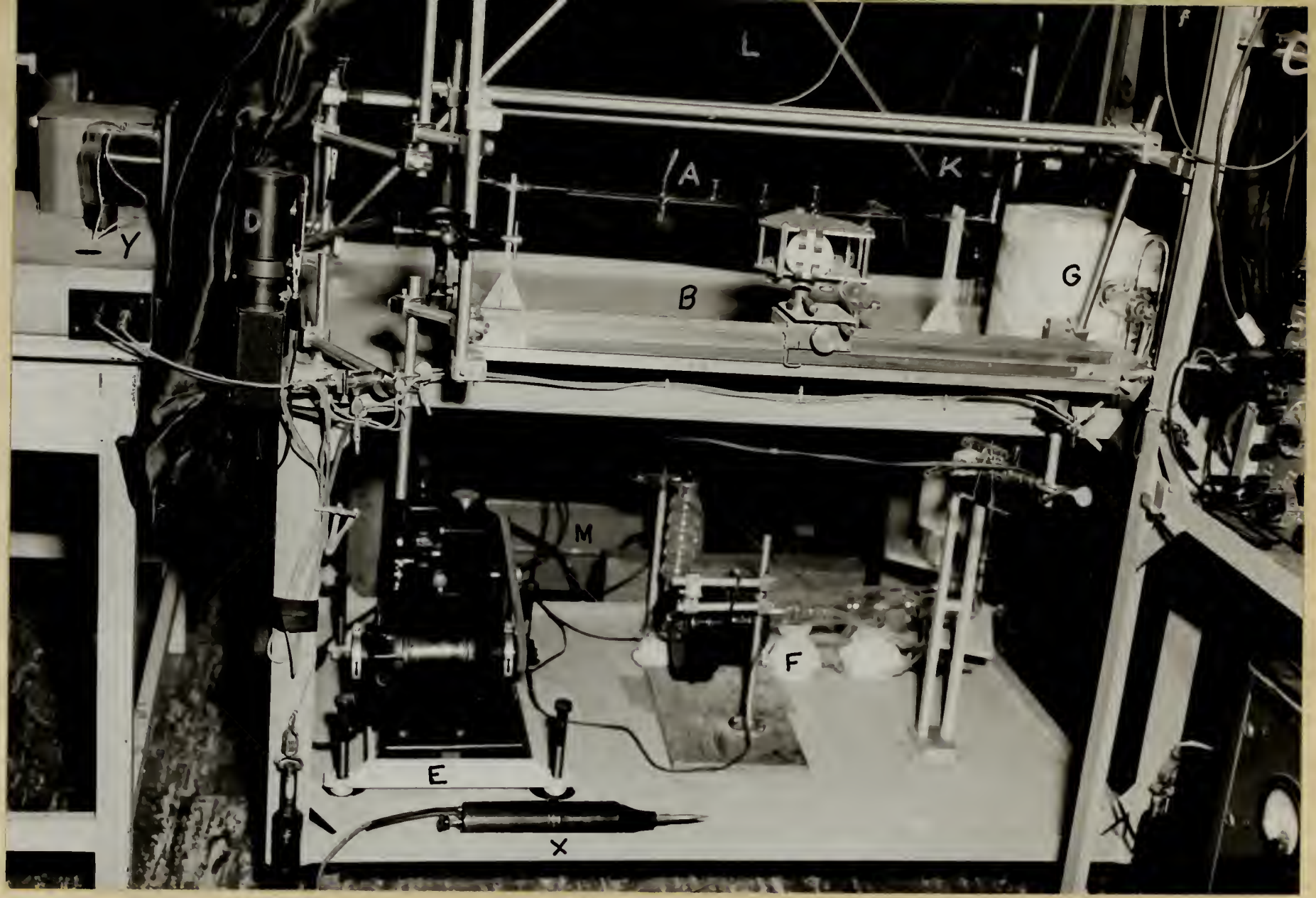


Fig. 3: Close-up of Discharge Tube With Probe Connected

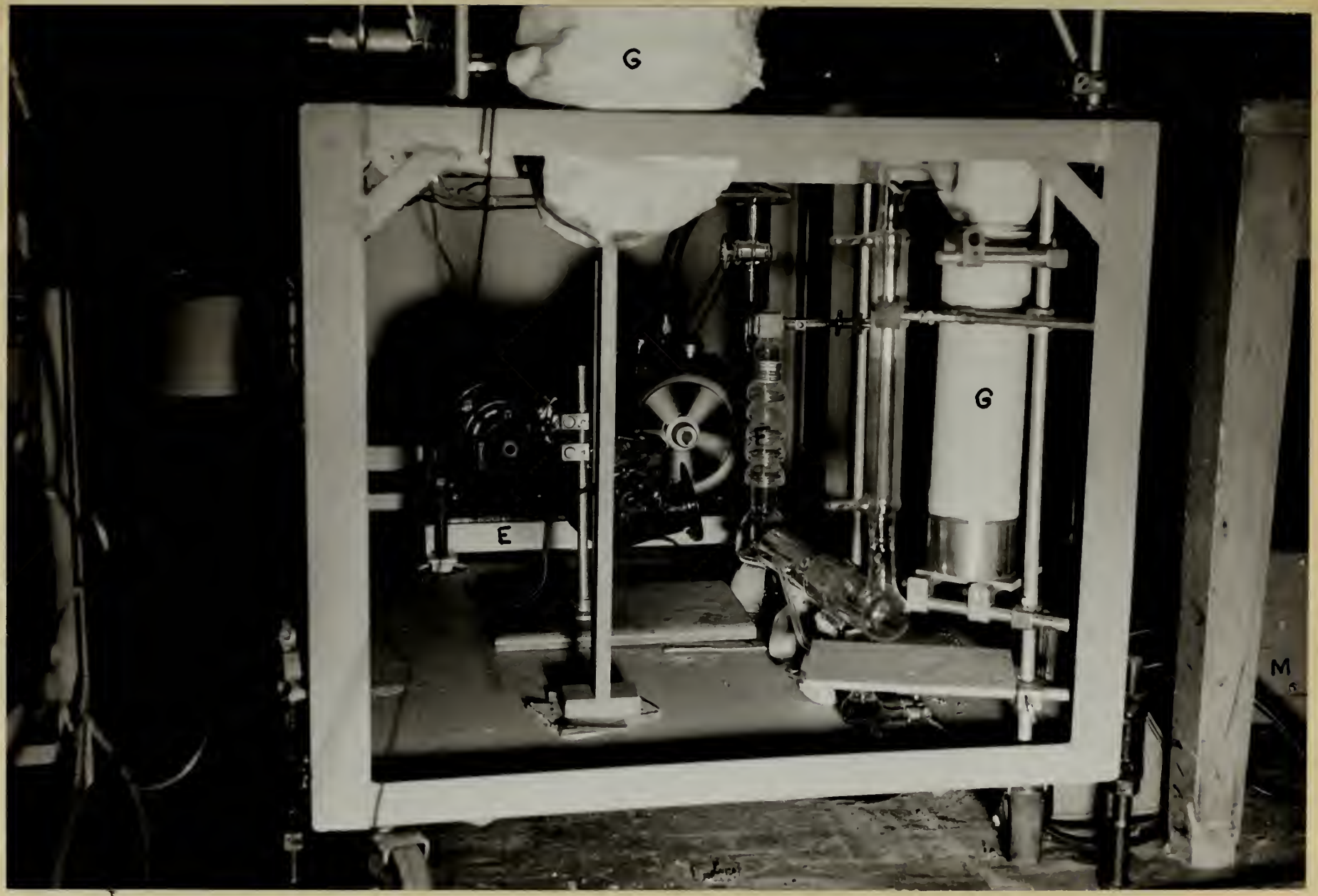


Fig. 4: Details of Vacuum Diffusion Pump and Forepump

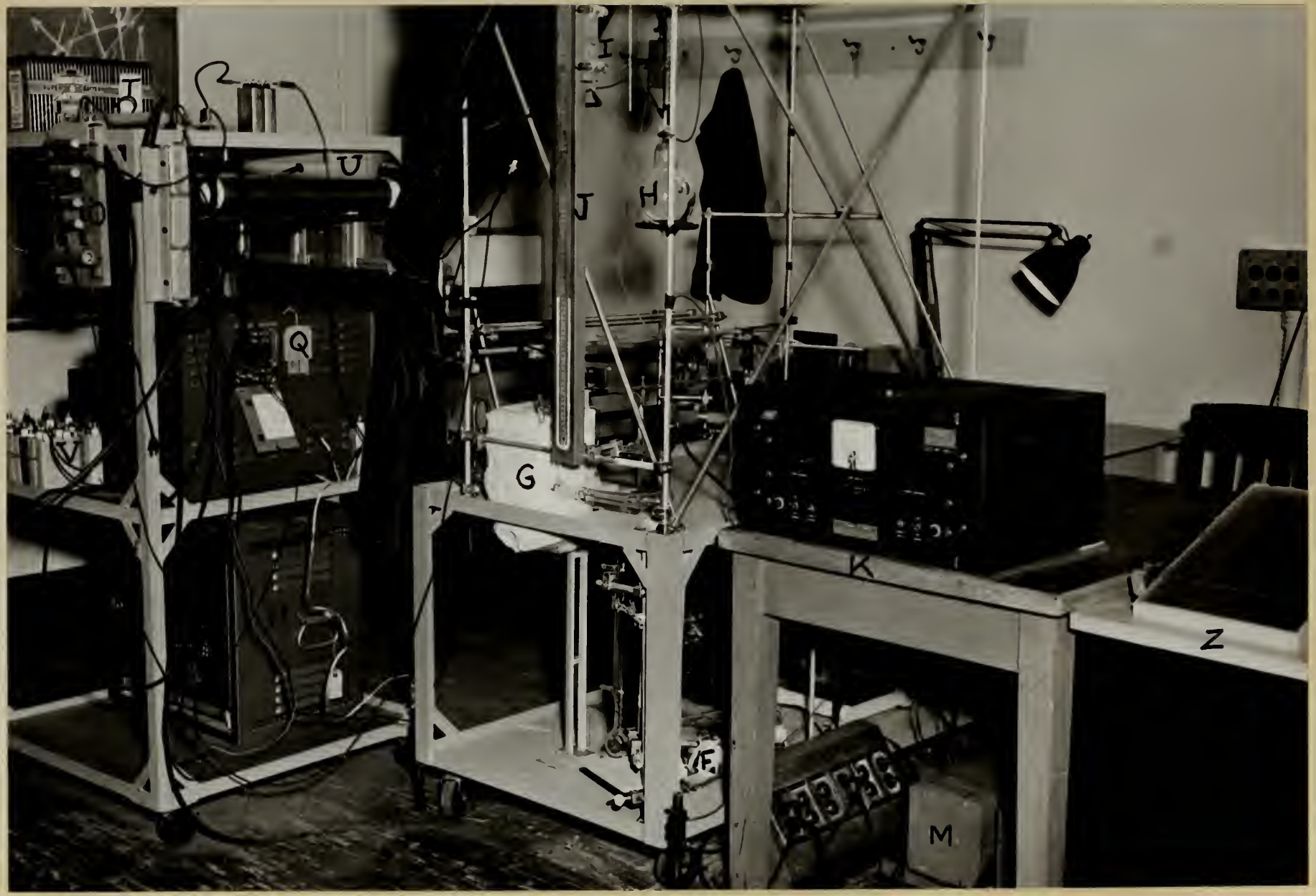


Fig. 5: Rear View of Apparatus

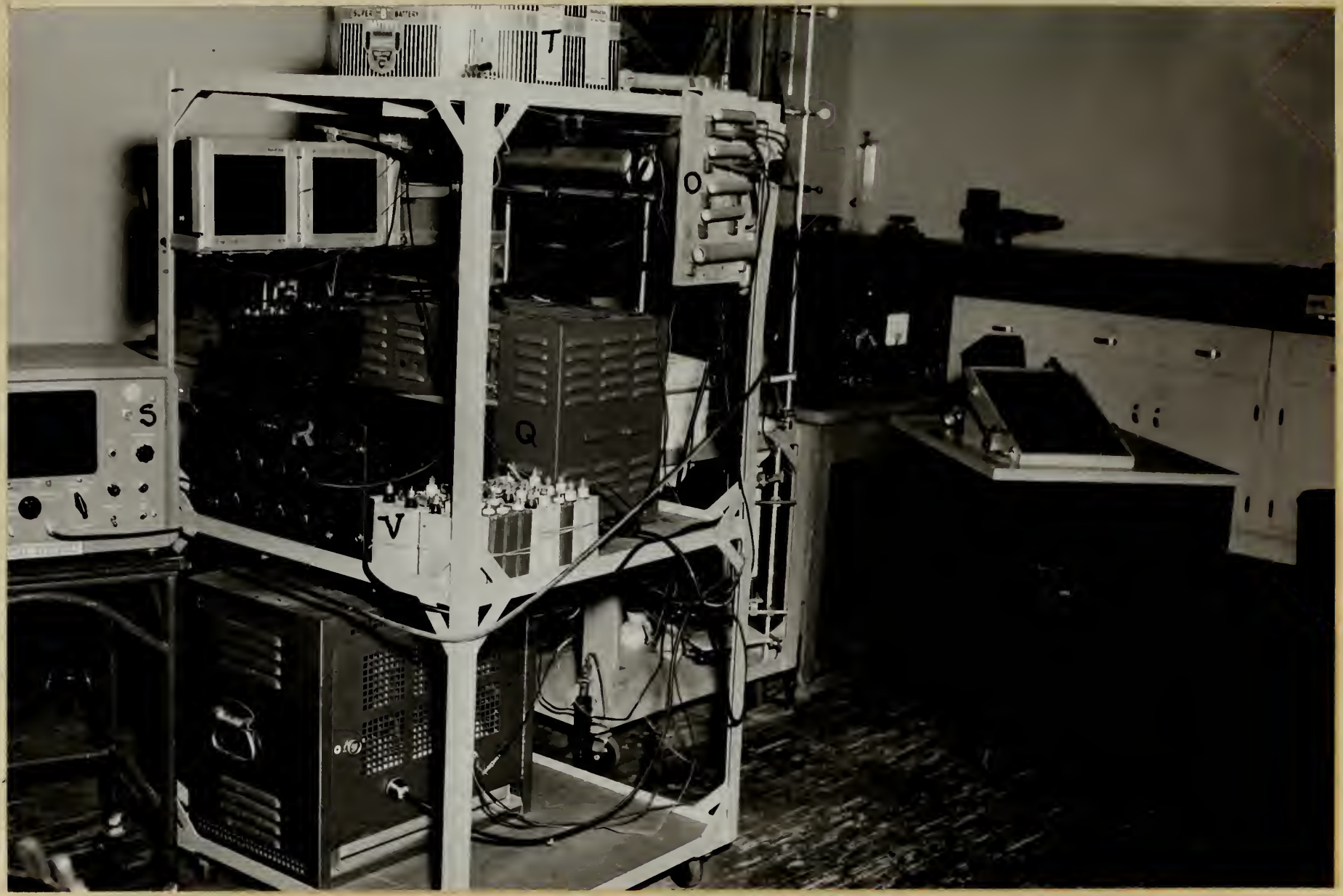


Fig. 6: Side View of Apparatus

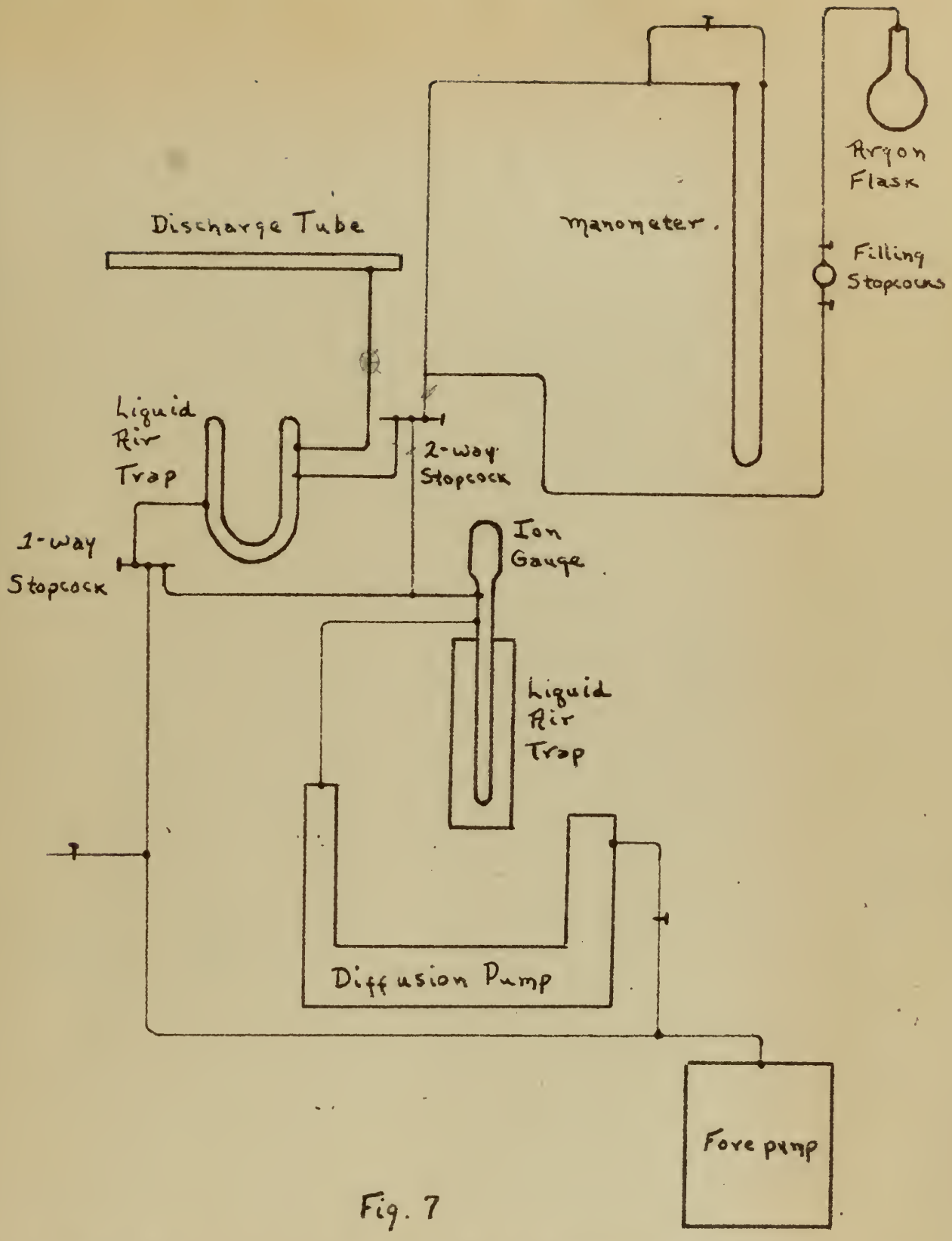


Fig. 7

Schematic Diagram of Discharge Tube, Vacuum and Filling Systems

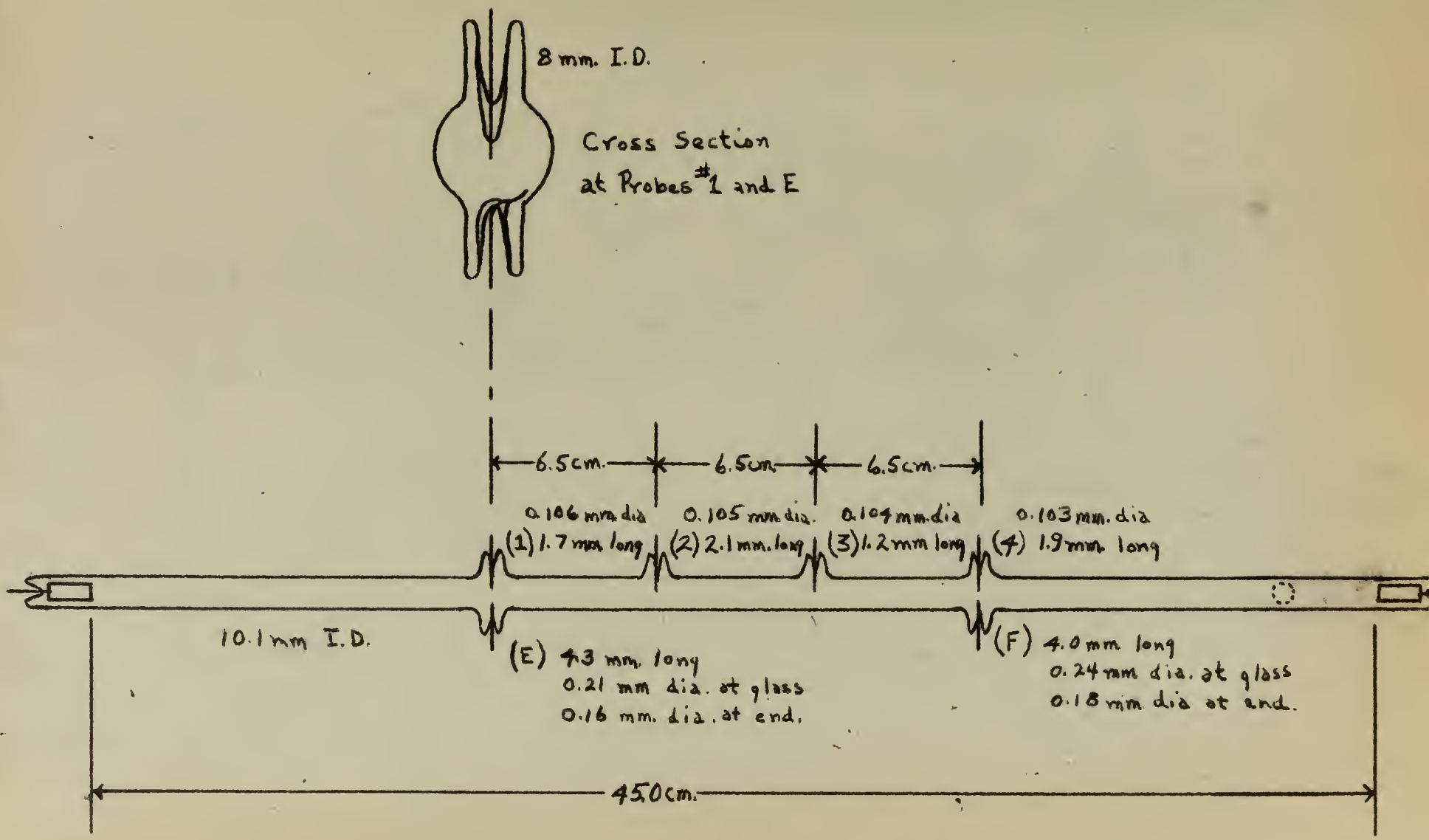


Fig. 8: Details of Discharge Tube

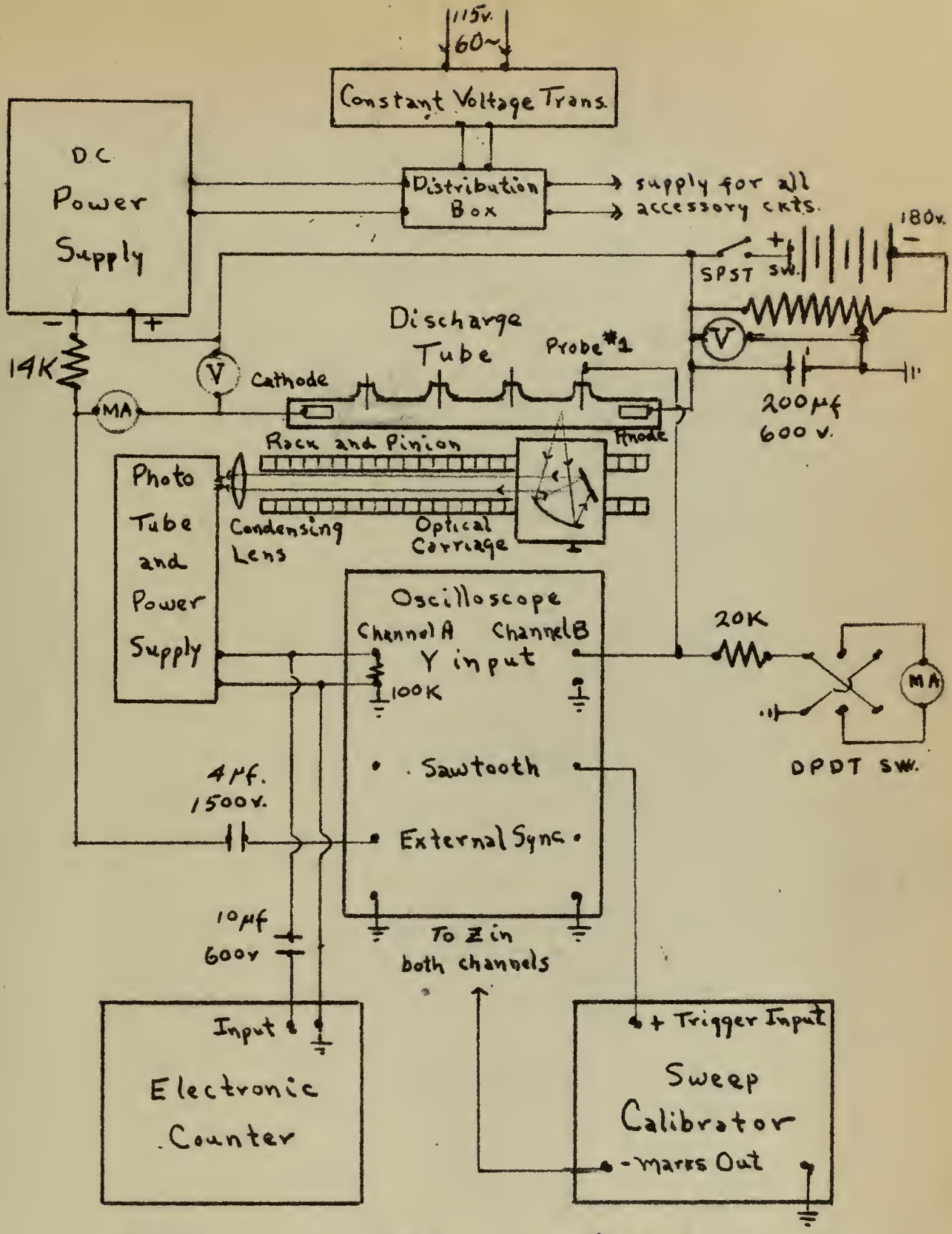


Fig. 9: Circuit Diagram of Apparatus

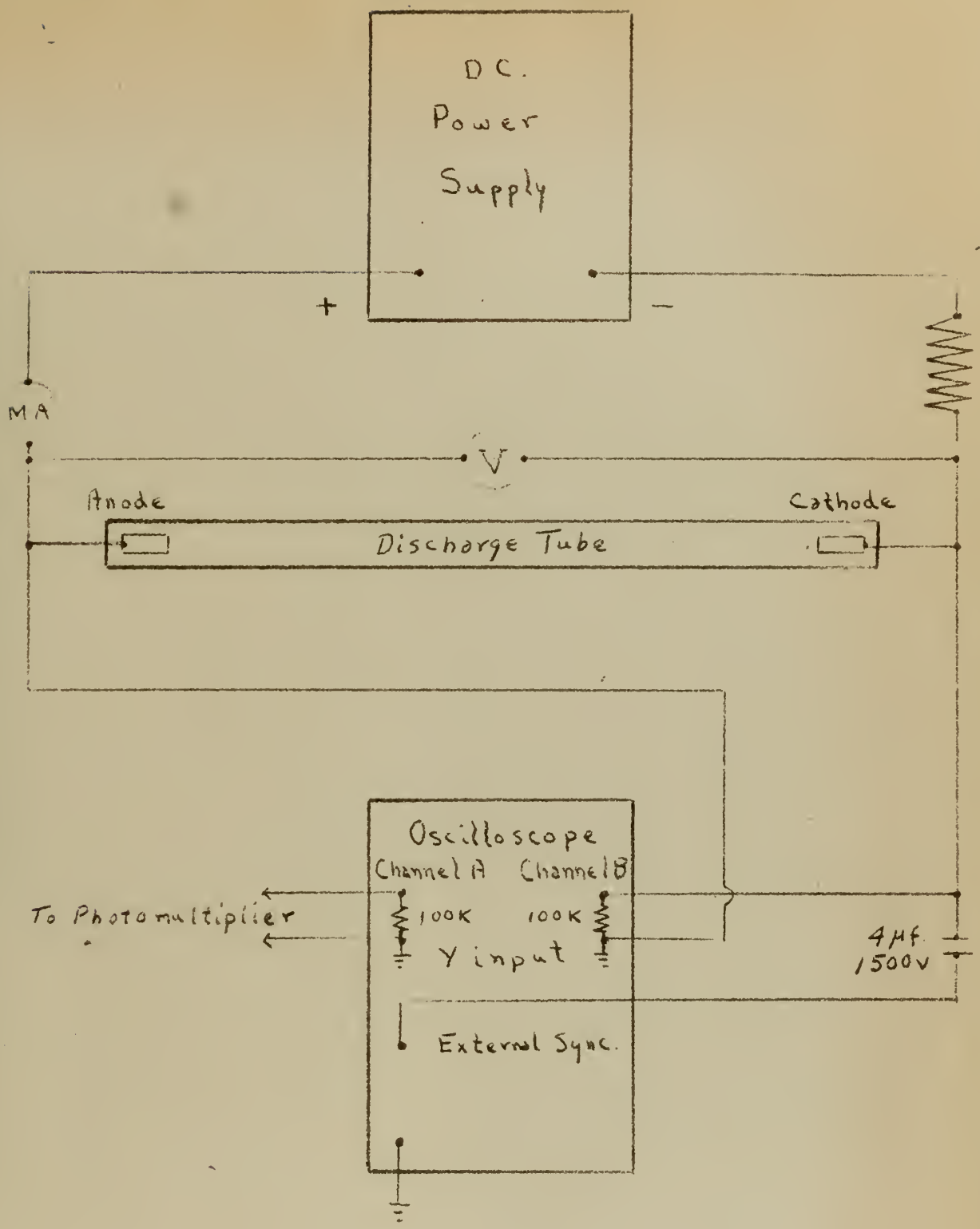


Fig. 10

Circuit Diagram for Voltage - Light Intensity Observation

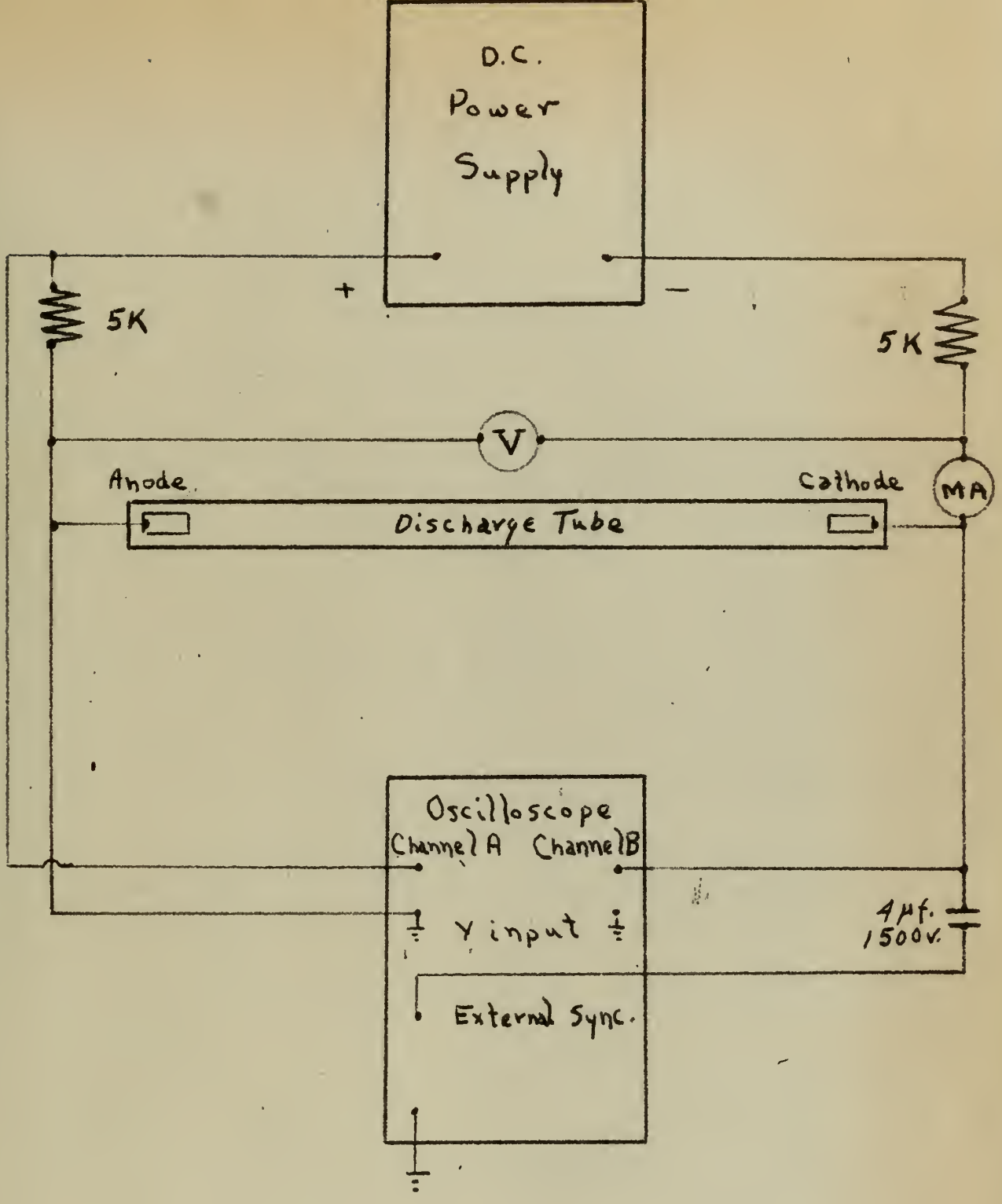


Fig. 11

Circuit Diagram for Voltage–Anode Current Observations

CHAPTER III

OBSERVATIONS AND ANALYSIS OF VARIATIONS IN VOLTAGE, CURRENT AND LIGHT INTENSITY

1. General Considerations

The variation in discharge tube voltage, current at the anode and cathode, and light intensity throughout the discharge glow in argon gas at 12 mm Hg. pressure were observed, by the methods of Chapter II, for a period of more than one month. During this interval the tube was operated daily for periods varying from about 4 - 16 hours, but no observations were recorded until after a minimum warm-up period of about four hours. Tube voltage and current were varied randomly at times but data were always taken for a series of increasing currents only. As reported by several writers[4,5,6,17,18] there is a definite hysteresis effect evidenced by different values of tube voltage and modes of oscillation at the same current depending upon whether the current was reached from an increasing or decreasing direction.

For the purposes of this report, a mode of oscillation is defined as those points which appear to be related (smooth curves between discontinuities) on a curve of frequency versus tube current. It has been reported that several modes may exist for the same value of current[4,5,6]. Some indications of such behavior were noted under unstable conditions during the warm-up period. However, a stated purpose of this study was the limitation of

observations to those under maximum possible conditions of stability. Under such conditions, no multiplicity of modes was observed, and all modes were frequently reproduced at will and without exception.

It must be emphasized, however, that this work was confined to the study of a d.c. discharge, in argon gas, at 12 mm. pressure, and in the one specific tube described in Chapter II. Moreover, except where otherwise stated, the observations were made with the external circuit shown in Fig. 9. The foregoing lends consistency but greatly limits the scope of the work and restricts the general applicability of the conclusions reached. Future investigations at other pressures, for different gases (particularly diatomic), and with different types of tubes will be necessary before any general conclusions may be reached. It is understood that a continuation of this work at the U. S. Naval Postgraduate School is contemplated, and suggestions for future investigation will be made in this paper where pertinent.

The range of experimental data is best illustrated by Figs. 13 and 14 which are plotted for the point in the positive column about 21 cm from the anode. Oscillations were always present, but for that region in which no solid curves have been indicated the oscillations were usually confused and no stable modes could be observed. The only consistent indication of such behavior was in the range from about 20 to 30 ma.

Several interesting tendencies may be noted from the curve of tube voltage and oscillation frequency versus tube current in Fig.

13. Neither voltage nor frequency is a continuous function of current. The voltage falls precipitously as the current is increased from about 11.8 ma. (the lowest value obtainable without extinguishing the discharge) to about 20 ma. Averaging the fluctuations in milliammeter and voltmeter readings during instability from 20 - 30 ma. as indicated by circled plots and dotted line, would appear to indicate that the voltage continued to fall to about 295 at 23 ma. and then rose abruptly to 306v at about 24 ma. where it again began to fall at about the previous rate. From 294v, at about 30 ma, the voltage continued to fall with increasing current but at a gradually decreasing rate until the limit of about 258v, at 105.3 ma, was imposed by the external circuit. This circuit was not modified to permit higher currents at the time since excessive sputtering was to be expected from the electrodes and it was more desirable to preserve the tube for further investigations. Observations at higher currents should be made when all other work with this tube is completed. Additionally, a tendency to drift toward increased voltages and decreased currents was observed at higher current settings of the external circuit as previously reported[6]. This was usually accompanied by a temporary instability of the oscillations.

The curves of oscillation frequency versus tube current are also plotted in Fig. 13 to facilitate comparison. It is believed that eight separate modes exist over the experimental range of currents. Apparently, under conditions of maximum possible stability, mode I decreases rapidly from 3780 - 3725 cps as the cur-

rent is increased from 11.8 - 13 ma. Mode II also decreases rapidly from 3484 - 3268 cps. as the current is increased from 14 - 19.7 ma. These may be the same mode since small adjustments between 13 and 14 ma. were not feasible with the available power supply.

The region from 19.7 - 30.3 ma. was unstable as described above, but averaging of the variations of the frequency indicated by the counter yielded the smooth curve shown by the circled plots and dotted line. Thus the graph depicts a continued and nearly infinite rate of decrease in frequency with increasing current during instability. From 30.3 ma. to the experimental limit, modes III - VIII are characterized by a gradual decrease in frequency with increasing current broken by small but definite jumps to higher frequencies at their discontinuities. Their ranges are:

Mode III	1653 - 1522 cps	30.3 - 47.8 ma.
Mode IV	1555 - 1524 cps	50.2 - 58.7 ma.
Mode V	1552 - 1503 cps	61.9 - 82.8 ma.
Mode VI	1514 - 1509 cps	85.6 - 91.3 ma.
Mode VII	1519 - 1513 cps	92.3 -100.0 ma.
Mode VIII	1524 - - cps	102.6 - ma.

Thus the frequency curve follows, in general the same trend as the voltage curve except for the discontinuities in the frequency curve due to moding; a tendency in the frequency curve to rise very slightly between modes at high currents; and a rise in the voltage curve at the beginning of instability. This latter fact may indicate that whatever mechanism causes this increase in voltage during instability does not similarly affect the fre-

quency of the oscillations.

For a more complete correlation, the curves of average velocity and average wavelength versus tube current are similarly plotted in Fig. 14. The values of wavelength used were obtained by dividing measured velocities by measured frequencies. These curves are not quite so simple as the frequency curve. The largest wavelengths are found for the lowest current modes. They increase with current for mode I from 3.18 to 3.23 cm. and drop to an essentially constant value of 3.0 cm. for mode II. Succeeding modes are characterized by abrupt small increases in wavelength which remain essentially constant for the particular mode:

Mode III	1.55 cm.
Mode IV	1.60 cm.
Mode V	1.65 cm.
Mode VI	1.70 cm.
Mode VII	1.75 cm.
Mode VIII	1.77 cm.

Average velocities, on the other hand, show a steady decrease from about 120 m/sec. at mode I and 113 - 102 m/sec. for mode II, but relative independence on current at about 25 m/sec. for all other modes above about 30 ma.

The results of these measurements for one pressure are not conclusive but tend to substantiate the belief that velocity curves reflect that part of the applied voltage which is due to cathode fall, while the frequency apparently follows the gradient in the positive column[6].

The character of the discharge conformed in general to that expected for the experimental conditions. These conditions were almost identical with those used by Dieke and Donahue[4,5,6].

The several characteristic regions of the discharge glow were discernable but not to an extent permitting accurate measurements of their limits. This was due, in part, to the metallic deposits on the inner walls of the tube near the electrodes incurred primarily during the degassing of the electrodes. This was a serious defect which also prohibited investigations at the electrodes. If practicable, further work should be done with this or a similar tube in which this defect has been eliminated.

Stationary striations were also visible in many instances, but were never sufficiently sharply defined to permit measurement and correlation with the moving striations as reported by Dieke and Donahue[4,5]. An objective of future work should also be to attempt to establish a relationship between stationary and moving striations as reported in the above work. As used in this paper, a striation is a marked variation in light intensity. Stationary striations remain at fixed positions in the discharge for a particular set of operating conditions. Moving striations are an oscillatory phenomena manifested by variations in light intensity with time and position. Those traveling toward the cathode will be called positive striations, while those traveling toward the anode will be called negative striations.

2. Comparison of Fluctuations in Tube Voltage, Light Intensity, and Electrode Currents.

These comparisons were made in order to test techniques for future work, and only a few measurements were made due to limitations on available time. Consequently only a few general remarks

can be made concerning the results obtained, and conclusions are only guesses from a very limited amount of data. The circuits of Figs. 10 - 12 were used with the double exposure oscillograph technique to obtain pictures of the type illustrated in Fig. 15. Further studies could also employ similar techniques to obtain direct comparisons of fluctuations in light intensity and electrode currents to verify reports that a current peak occurs whenever a moving striations is seen at the cathode, and that a maximum in the tube voltage and a current minimum occurs when one is seen arriving at or leaving the anode[4,5]. Observations were made for only one external circuit arrangement with 5,000 ohms resistance at each electrode since instability resulted for values of total external resistance outside the range from 10,000-15,000 ohms. Future investigation should also be made for several values of external resistance to verify observations by other workers that electrode current fluctuations are identical, except in amplitude, for any permissible values of external resistance at anode and cathode. These workers further report that electrode currents vary in such a way as to keep the magnitude of the voltage oscillations constant at peak to peak values approximately equal to the excitation and ionization potentials of the gas[4,5].

The traces of Fig. 15 were made with external synchronization due to triggering by peaks in voltage variation at the cathode as were all oscillograph pictures in this report. Figs. 15A - D illustrate the fact that tube voltage fluctuations have the same frequency and a constant phase relationship with the light in-

tensity variations for any given point in the discharge glow as stated in Chapter II. Due to the polarity of the photomultiplier circuit, increasing light intensity is represented by increasing vertical distance, to an arbitrary scale, in the downward direction from the upper zero trace (as is the case throughout this report). It is readily seen that the light intensity undergoes a large amount of modulation. However, throughout all our observations, the light intensity never fell to zero in the minima as reported by Dieke and Donahue[5]. The lower trace of Figs. 15A - D depict the variations in tube voltage, about the average value shown by the horizontal trace, to a scale of 143v per vertical square positive in the downward direction. Since this average value is in the order of 300 volts (actual values are given in figures), it is clear that the voltage variations are modulated by only less than one percent. It was also noted that both voltage and light intensity oscillations become erratic together under conditions of instability. Of considerable speculative interest is the complexity of the voltage waveform with several subsidiary peaks. It would also appear that a dip in the voltage coincides with a maximum in the light intensity near the cathode (Figs. 15B and C), but that the largest dip does not necessarily coincide with the greatest intensity maximum as reported by Dieke and Donahue[4]. Since the tube current is at a maximum when the tube voltage is at a minimum, this means that current surges accompany the presence of striations near the cathode; but that the greatest current surges do not necessarily coincide with the striation

maxima. Further investigations of this nature should be made along with similar observations at the anode where striation maxima should coincide with voltage maxima. It should also be noted that in all instances the peak to peak change in tube voltage is approximately the first critical potential of argon, 11.57 volts.

Figs. 15E and F compare tube voltage oscillations (upper traces) with currents at the electrodes (lower traces). Again the same periodicy and constant phase relationship are demonstrated. In Fig. 15E positive maximum in tube voltage oscillations, about an average of 282v., is in the downward direction as before; while anode current variations, about an average of 32.0., have a positive maximum in the upward direction and have a peak to peak value of about 3 ma. As is to be expected, the waveforms are identical except in amplitude. Note particularly that the current is apparently leading the voltage in phase. Fig. 15F is similar except that positive maximum voltage variations, about an average of 274., are now represented in the upward direction, due to the nature of the circuits shown in Fig. 11 and 12; and the current at the cathode oscillates about an average value of 35.0 ma, with maxima also in the upward direction, which have a peak to peak value of about 2.24 ma. The current here appears to lag the voltage in phase. This would appear to be inconsistant with the work of Dieke and Donahue[4] but further observations must first be made. If correct, this would indicate a phase shift within the tube which must be explained by any theory concerning

the discharge.

3. Studies of Moving Striations

The oscilloscope patterns of the time variations in light intensity in the glow were observed for many hours at various modes of oscillation. Variations in position along the glow were introduced into the data for analysis by taking a series of oscillograph pictures at various positions along the tube for the same mode (as evidenced by continuous frequency monitoring). Typical pictures for three modes are shown in Figs. 16 - 18. As previously discussed, the oscillograph was externally synchronized with the oscillations in tube voltage, and light intensity maxima are in the downward direction from an upper zero trace. Thus positive striations are detectable by light intensity maxima which occur later in time as the optical carriage is moved toward the cathode and conversely for negative striations. The time markers indicate 100 microsecond intervals increasing in time from left to right. For any stable mode of oscillation, moving striations were detectable at all points in the discharge glow, and their behavior can be studied as a function of the various discharge parameters. Considerable more work in this respect remains to be done both with the same tube and pressure and with other tubes, gases, and pressures.

Assuming the validity of the principle of superposition, negative striations would be evidenced as attenuations in the amplitude of the intensity traces of the comparatively more prominent positive striations since a neutralization and resulting diminution

of light intensity would occur whenever a positive and a negative space charge are in space and time correspondence. Further, the "antipeaks" of such attenuations should travel toward the anode at speeds very much greater than the cathode bound positive striation since they are due to migrations of electrons with a very much smaller mass and greater mobility than the positive ions of the positive striations. Such behavior was actually found to occur. In our investigations the movement of "small intensity peaks", due to negative striations, toward the anode was never observed although this has been reported by Dieke and Donahue[4]. Again, this discrepancy may not be construed as conclusive since it is based on a very few observations of limited scope.

The intensity pattern may be quite different for different modes as may be seen in Figs. 16 - 20. Mode II at 18.8 ma., 298v, and 3346 c.p.s. is shown in Fig. 16 at varying distances from the cathode. Fig. 16A is typical of all light intensity traces in the positive column. The attenuation due to a negative striation becomes noticeable in Fig. 16B, and succeeding pictures are typical of such attenuation as the cathode is approached. The attenuation is apparently due to only one negative striation. The overall reductions in intensity near the cathode are at least in part due to the metallic coating on the inner walls of the tube from sputtering.

Mode III is depicted in Fig. 17 from near the anode (A-C) to near the cathode (D-F). Again, overall alternation near the electrodes is at least partially due to metallic deposits on tube

walls in the vicinity of the electrodes.

Fig. 18 shows the similar behavior of Mode VII. Inside the positive column (A) the attenuations due to negative striations are not conspicuous and their amplitude must be small. Near the cathode (B-F) the intensity pattern changes greatly due to increases attenuation by the negative striation as discussed above.

To determine the direction and approximate average velocity of the negative striation, a group of pictures were selected for analysis of the direction and average velocity of the attenuation "antipeaks" of the positive striation as produced by the negative striation. A set of 12 pictures (2.01 - 0.84 cm. from the cathode) for Mode V at 61.0 ma, 256v. and 1507 c.p.s. best illustrate this phenomen and are contained in Fig. 19 and 20. The analysis of these figures also holds qualitatively for all other modes observed. An arbitrary zero reference time was selected (marked "O" on each picture); and, since the oscillograph sweep speed was not changed during the series, the distance between vertical grid lines was computed to be equal intervals of 115 microseconds each. Total time increases from left to right.

A cursory examination of this series would indicate that, near the cathode, subsidiary peaks arise spontaneously and occur at approximately the same time for a short distance along the discharge glow. Several sets of such subsidiary peaks have been marked with asterisk (*) in the figures. It is believed, however, that such peaks are merely points on the positive striation waveform at which attenuation by a second waveform becomes apparent.

It shoud also be noted that none of these subsidiary peaks have any apparent motion toward the anode as would be evidenced by their occuring at an earlier time when the optical carriage is moved toward the cathode (as in this sequence).

A more careful analysis of these waveforms therefore indicates that they are composites of two (or possibly more) components. The most prominent component is that due to the positive striation mode, and the amplitude of this component is probably a periodic function of time which is essentially the same (except for phase and possibly maximum value) for any position in the glow.

The second component is most readily identified by the maximum attenuation which it produces in the more prominent positive striation mode waveform. A rigorous analysis, such as a Fourier analysis, of this composite waveform would be helpful but is beyond the scope of this report.

Again considering Figs. 19 and 20, positive striation peaks which are essentially unaffected by a second waveform have been marked (+), and "antipeaks" resulting from maximum attenuation of the positive striation by a second waveform have been marked (-).

An "antipeak" first occurs at measureable times of 103 and 1369 microseconds in Fig. 19A. They have been designated as "antipeaks" (a-) and (a'-) in this and succeeding pictures since they are apparently manifestations of the same secondary waveform on alternate cylces of the composite. It is further believed that these "antipeaks" are the most reliable indications of the maxima of this second component, since maximum attenuation of the positive

striation and consequent maximum diminution of the light intensity should occur at the maxima of a second component which apparently has a neutralizing effect. A complete graphical analysis of the resulting composite waveform is also beyond the scope of this paper, but a simplified "time-position" analysis of these "anti-peaks" should reveal the direction and approximate velocity of this second component. A careful determination of the time in microseconds at which they occur for the positions in the glow discharge illustrated in Fig. 19 and 20 was made on the photoreader, and are listed below with the computed average velocity (V) in m/sec.

TIME-POSITION MEASUREMENTS OF "ANTIPEAKS"

Figure	Cm from Cathode	a- Time	a- V	a'- Time	a'- V	b- Time	b- V	b'- Time	b'- V
17A	2.01	103		1369					
17B	1.87	92	165	1358	156				
17C	1.73	86	158	1351	158				
17D	1.68	80		1346					
17E	1.62	80		1346					
17F	1.50	80		1346					
17G	1.44			1133					
17H	1.38			1121					
18I	1.30			1121		564		1829	
18J	1.13			1121		529	71	1806	100
18K	1.01			1121		523		1800	

It is thus seen that "antipeaks" (a-) and (a'-) occur earlier in time as the cathode is approached and therefore are traveling from the cathode toward the anode. Their average velocities, where measureable, are approximately 160 m/sec., or about six times previously determined velocity of about 25 m/sec. for the positive striations at this mode of oscillation. This direction

and comparatively high velocity would appear to substantiate the belief that this second component is due to negative space charge clouds of electrons which will be called a negative striation.

In Figs. 19A and B these negative striation maxima ("antipeaks") are seen to have relative movement toward the positive striation maxima at their left. A "time-position correspondence" of both component maxima is indicated in Fig. 19C. Then in Fig. 19D - F the relative movement continues toward the positive striation minima at the left. At 1.44 cm. from the cathode (20G), this relative movement has progressed past the positive striation minima and the left "antipeak" is now the one due to negative striation neutralization since the positive striation clearly cannot be neutralized below its minimum intensity. Of greatest interest is the observation that "antipeak" (a'-) occurs at 1346 microseconds in Fig. 19F and at 1133 microseconds in Fig. 20G, which is only 0.06 cm. closer to the cathode. This would lead to an average velocity of only about 3 m/sec. at the point where a negative striation maxima coincides with a positive striation minima or, in other words, the negative striation essentially stops for a period of about 200 microseconds and then continues its motion as before.

In Fig. 20G negative striation "antipeak" (a-) moves off the screen but the first indication of a second pair of "antipeaks" may be noted. In succeeding pictures the progress of "antipeak" (a'-) may be followed as before, and a similar analysis of "antipeaks" (b-) and (b'-) reveals that they also move from cathode to

anode but at an approximate average velocity of 80 m/sec. or about 3 times that of the positive striations.

Also worthy of comment is the observation that these positive and negative striations apparently have a harmonic relationship as evidenced by the symmetry of the composite waveform and the similarity of alternate cycles.

Except by an elaborate mathematical or graphical analysis, the positive striation velocities for these pictures cannot be reliably determined since the negative striations mask the positive striation intensity peaks. It is logical to presume, however, that the positive striation velocity is of the same order as before but is also affected during the neutralization process in a manner similar to the "stopping" of the negative striation. Thus this "meeting" or neutralization phenomenon may form stationary regions of true plasma which could give rise to stationary striations at such "meeting" points in the positive column of the glow discharge. The light intensity at such points would have a higher time average value, and thus appear brighter, even though instantaneous values of light intensity are greater at the positive striation maxima.

The foregoing method of analysis differs considerably from that of Dieke and Donahue[4,5,6], but the conclusions reached are essentially the same. It must again be emphasized, however, that this analysis is based on extremely limited observations, and considerably more work must be done before any definite conclusions may be made.

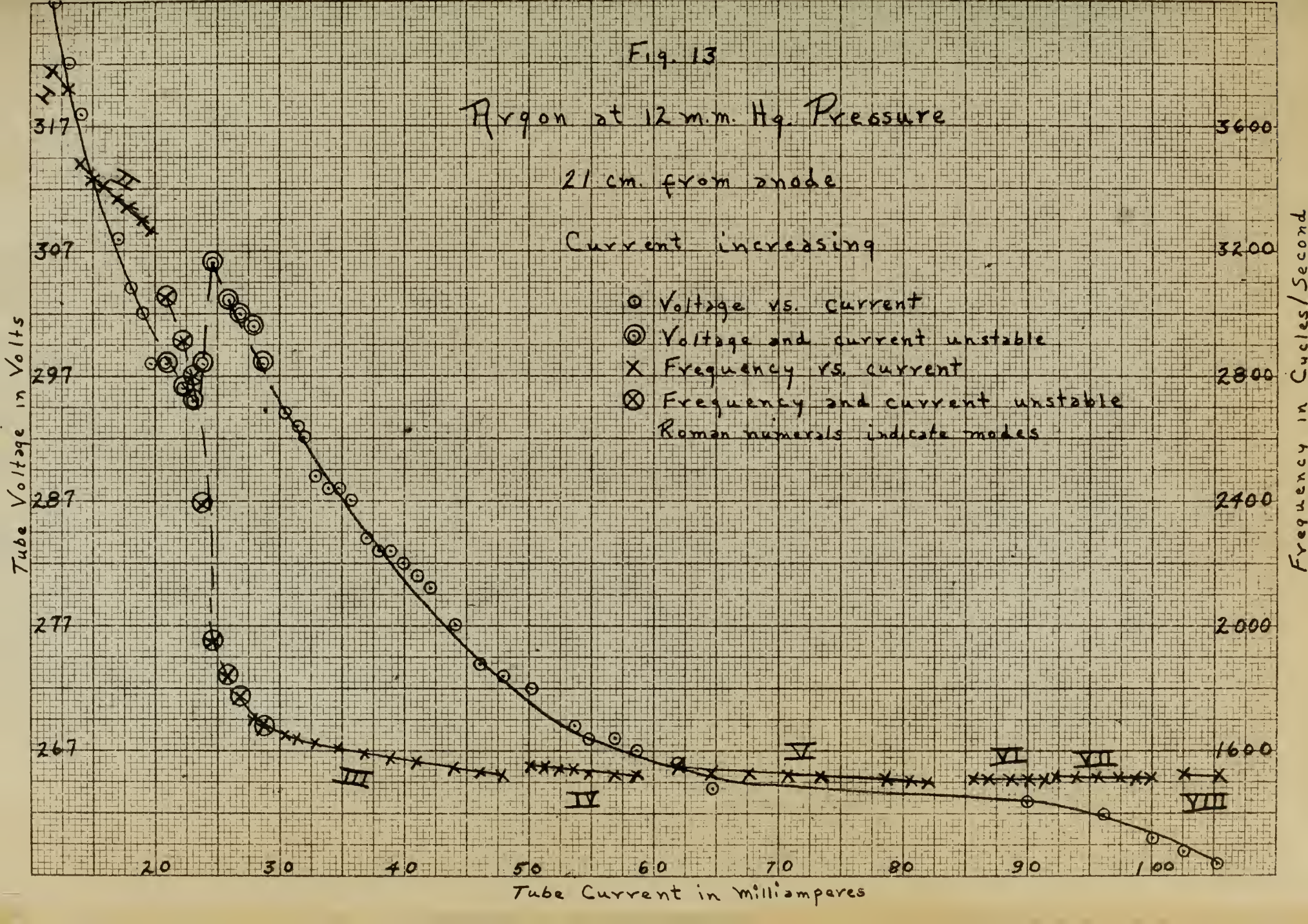


Fig. 13
Argon at 12 m.m. Hg. Pressure
21 cm. from anode
Current increasing
⊙ Voltage vs. current
◎ Voltage and current unstable
× Frequency vs. current
⊗ Frequency and current unstable
Roman numerals indicate modes
Tube Voltage in Volts
317
307
297
287
277
267
Frequency in Cycles/Second
3600
3200
2800
2400
2000
1600
II
III
IV
V
VI
VII
VIII
20
30
40
50
60
70
80
90
100
Tube Current in milliamperes

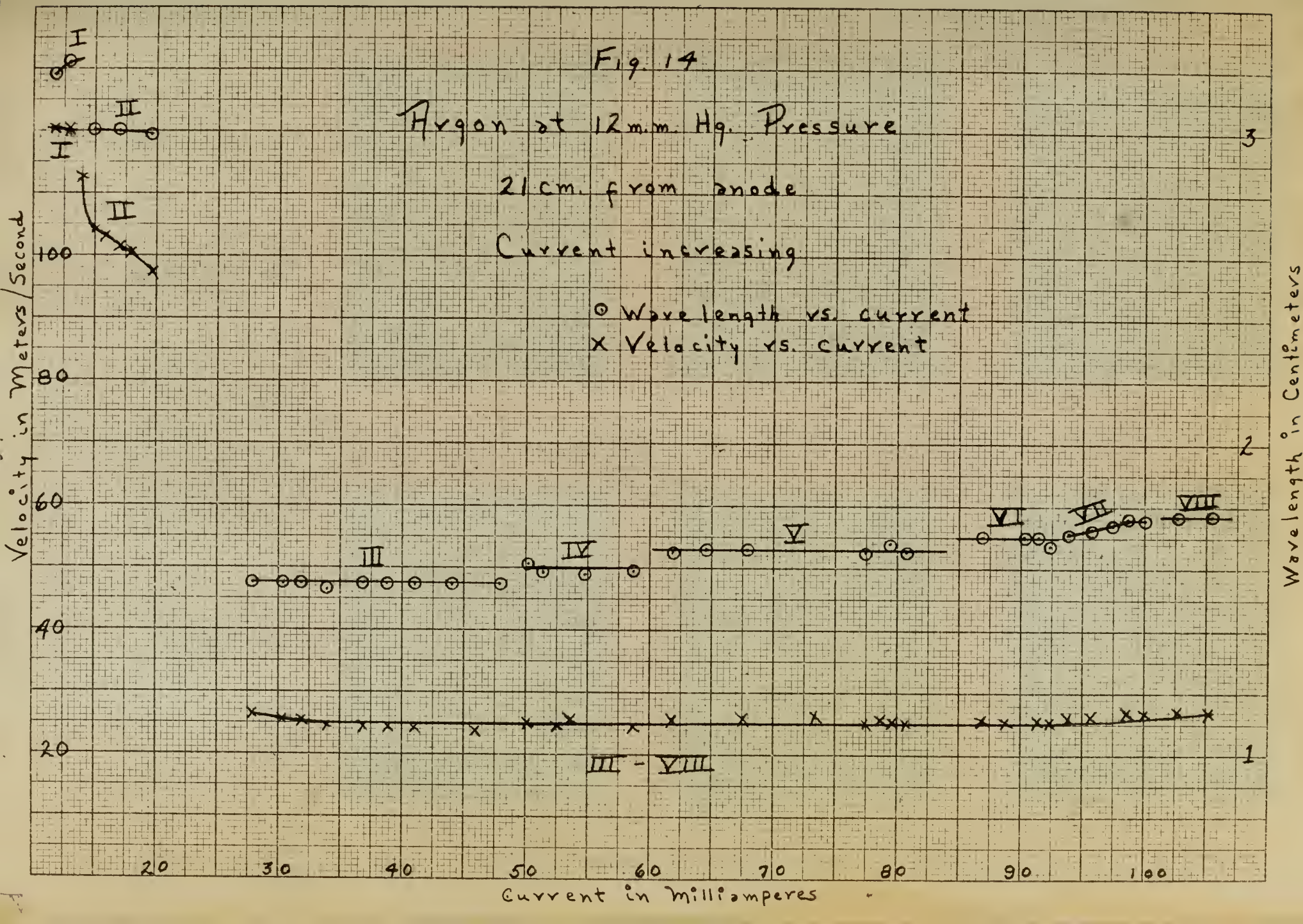
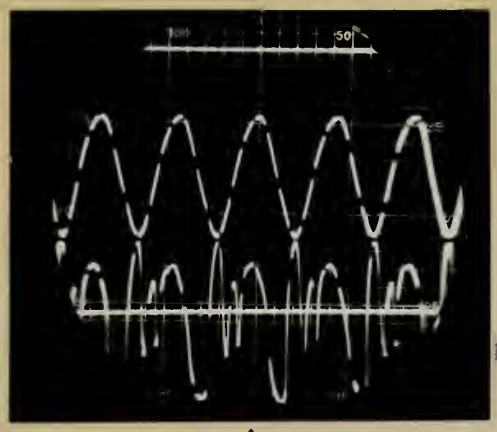
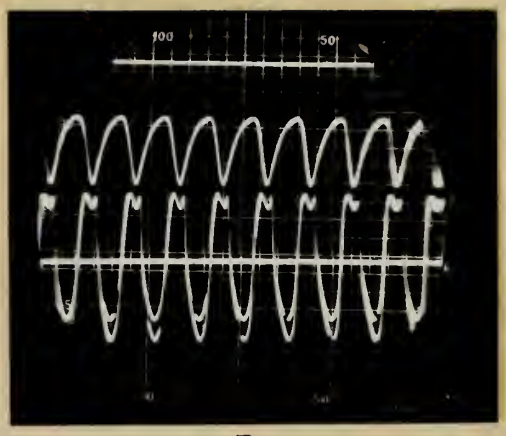


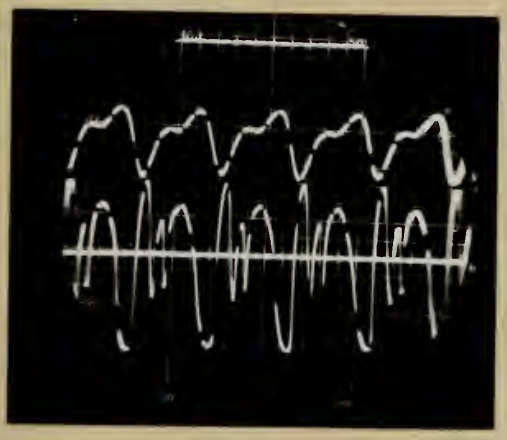
Fig. 14
Argon at 12 m.m. Hg. Pressure
21 cm. from anode
Current increasing
⊙ Wave length vs. current
× Velocity vs. current
Velocity in Meters/Second
Wavelength in Centimeters
Current in milliamperes
I
II
III
IV
V
VI
VII
VIII
III - VIII
20
30
40
50
60
70
80
90
100
40
60
80
100
1
2
3



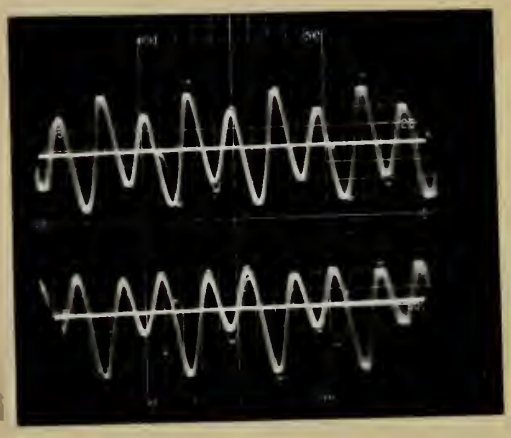
A



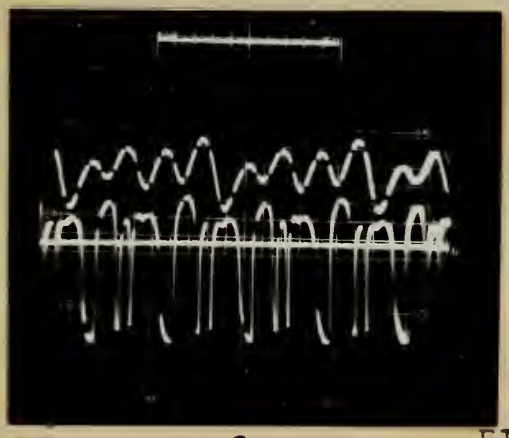
D



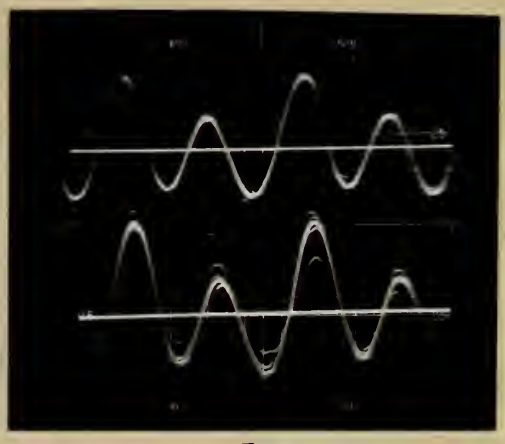
B



E



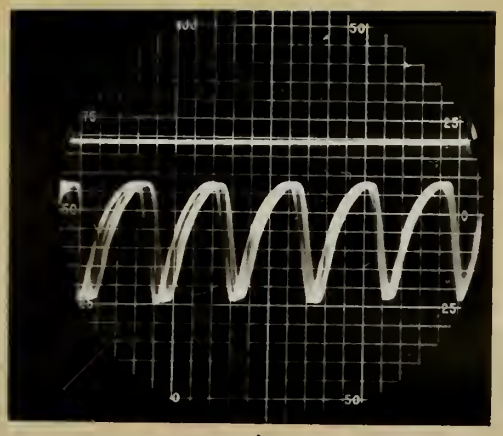
C



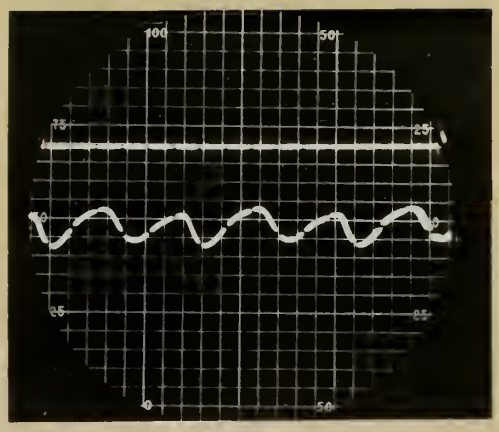
F

FIGURE 15

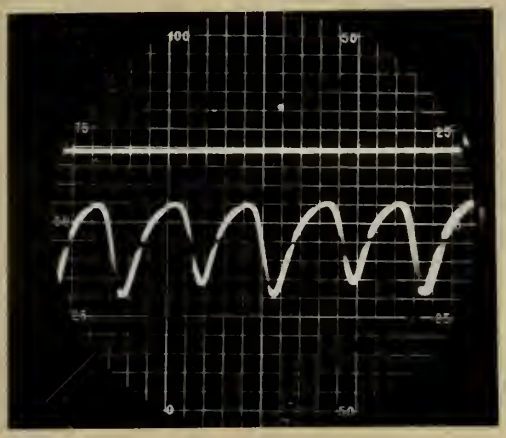
Comparisons of Fluctuations in Current, Voltage, and Light Intensity
Upper trace is light intensity; lower trace is tube voltage(1.43v/sq)
A: 18.9 cm. from anode; 50.4 ma.; 262v.; 1507 c.p.s.
B: Same as A except at 1.0 cm. from cathode.
C: 1.0 cm. from cathode; 93.2 ma.; 246v.; 1536 c.p.s.
D: 3.33 cm. from cathode; 13.8 ma; 312v.; 3491 c.p.s.
Upper trace is tube voltage; lower trace is electrode current.
E: 32.0 ma.; 282v.; 3710 c.p.s.; 3.33 v./sq; 0.5 ma./sq. at anode.
F: 35.0 ma., 274v.; 1840 c.p.s.; 4.35v./sq.; 0.28 ma./sq at cathode



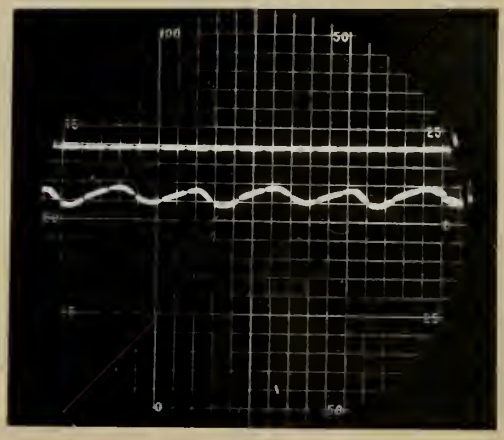
A



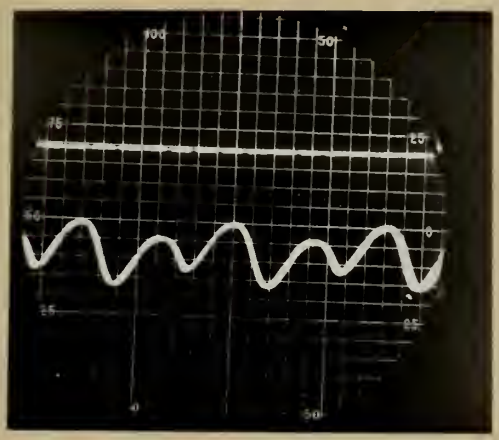
D



B



E



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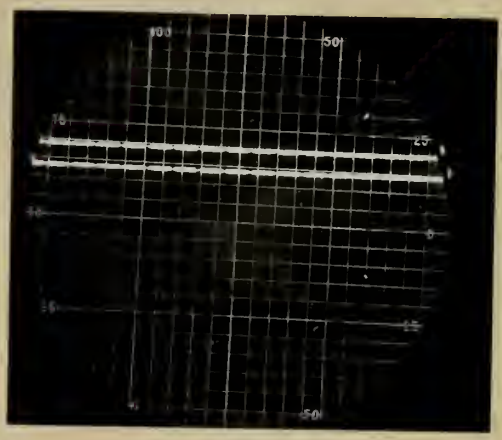


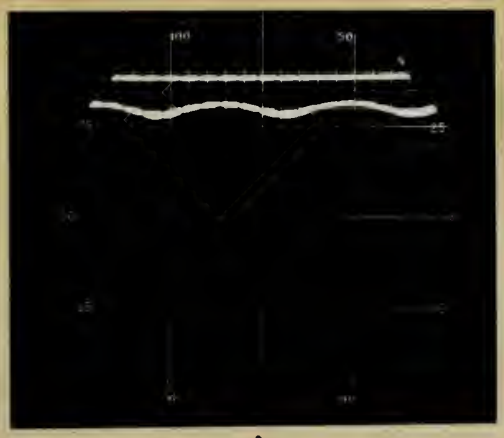
F

FIGURE 16

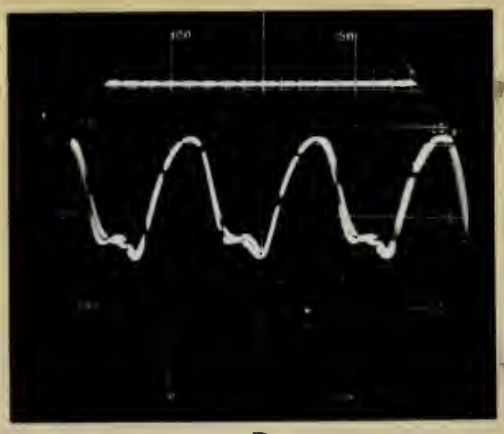
Light Intensity Fluctuations at 18.8 ma, 298v, 3346 cps (Mode II)

A: 6.46 cm from cathode
B: 1.61 cm from cathode
C: 1.1 cm from cathode
D: 0.84 cm from cathode
E: 0.72 cm from cathode
F: 0.27 cm from cathode

(Maximum intensity is in downward direction from upper zero trace)



A



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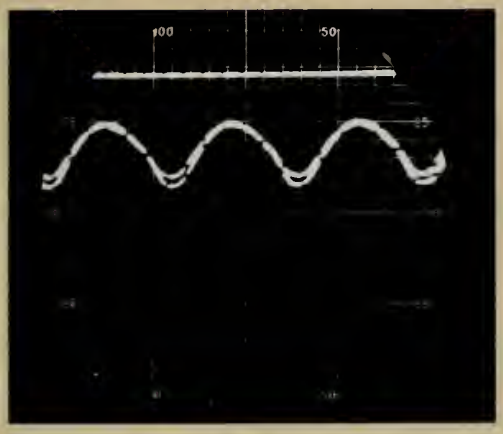

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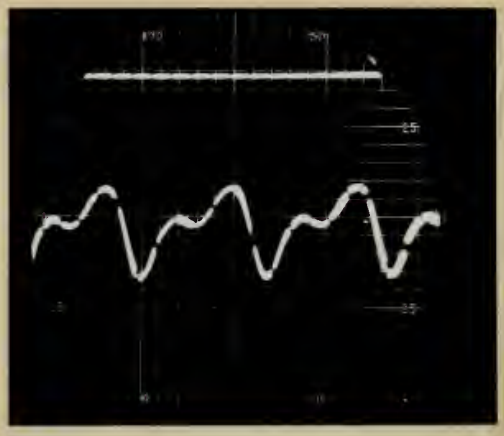

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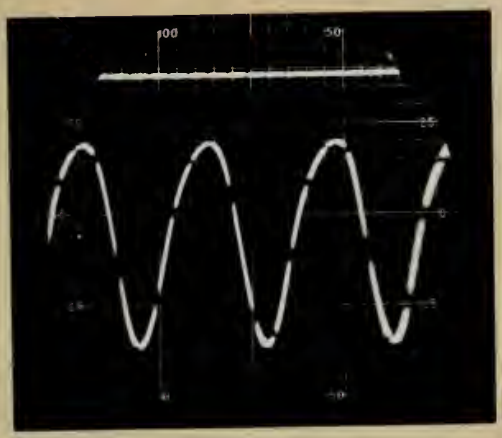

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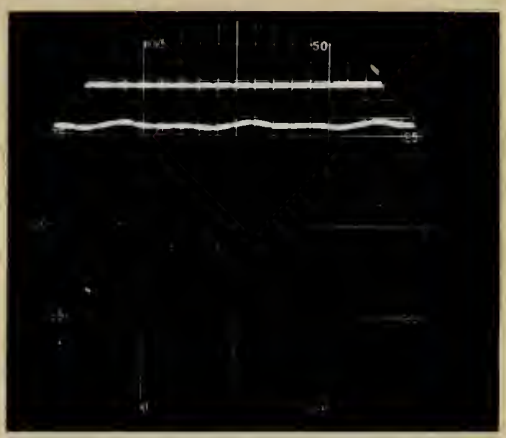


F

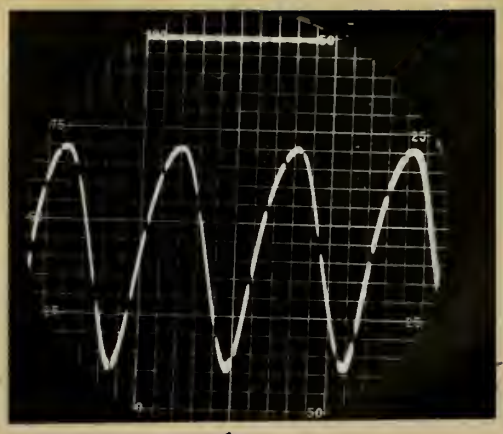
FIGURE 17

Light Intensity Fluctuations at 45 ma, 272.5v, 1533 cps (Mode III)

A: 0.35 cm from anode
B: 0.64 cm from anode
C: 5.64 cm from anode

D: 1.71 cm from cathode
E: 0.98 cm from cathode
F: 0.57 cm from cathode

(Maximum intensity is in downward direction from upper zero trace)



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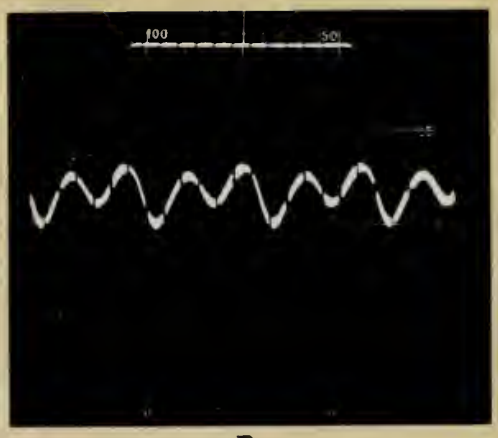

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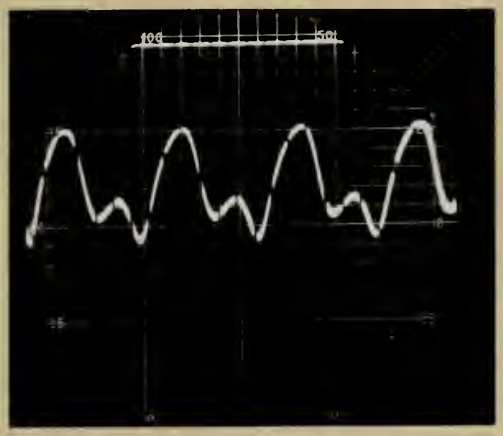
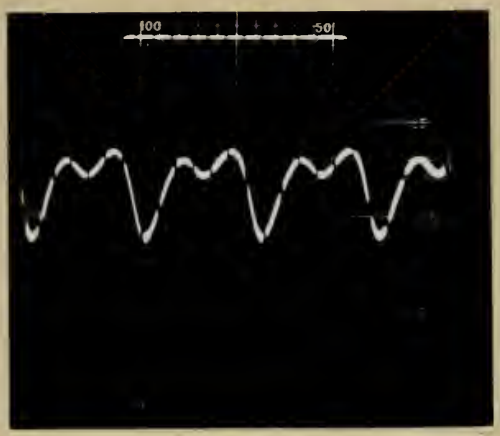


B

E



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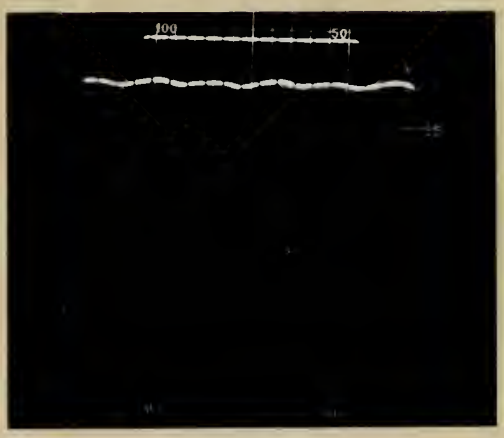


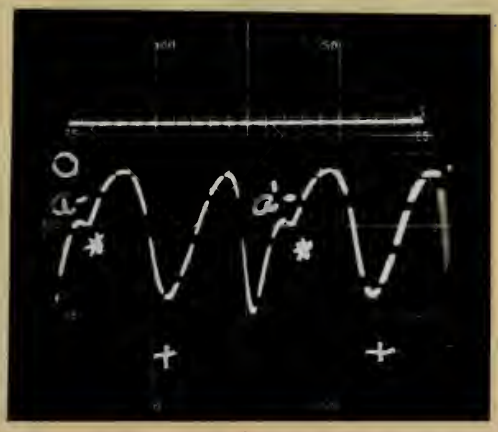
F

FIGURE 18

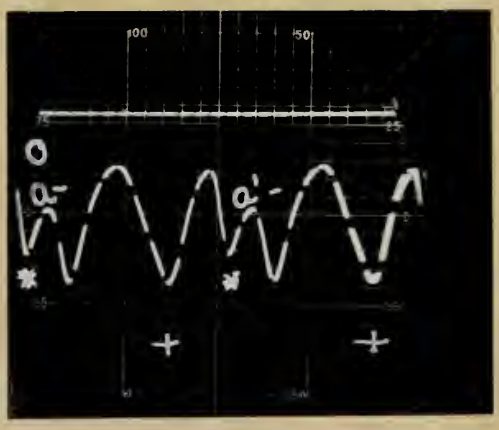
Light Intensity Fluctuations at 95.0 ma, 253v, 1499 cps (Mode VII)

A: 12.25 cm from cathode
B: 1.61 cm from cathode
C: 1.2 cm from cathode
D: 0.86 cm from cathode
E: 0.76 cm from cathode
F: 0.61 cm from cathode

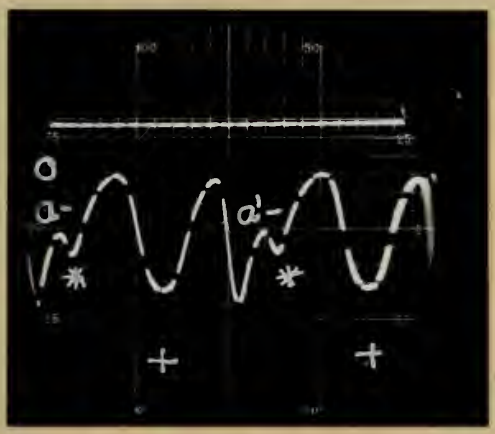
(Maximum intensity is in downward direction from upper zero trace)



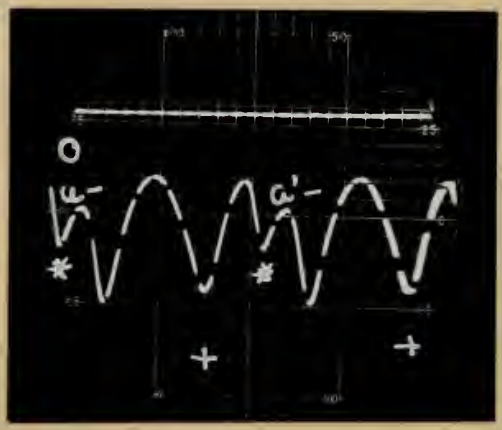
A



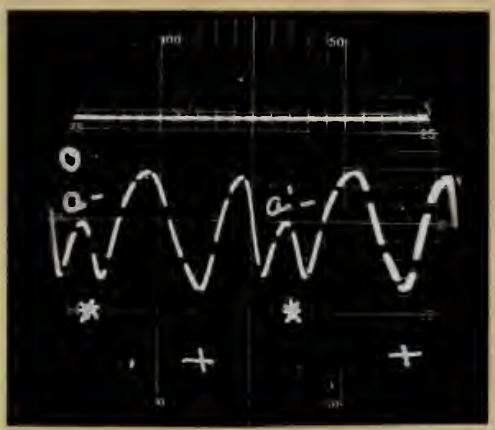
D



B



E



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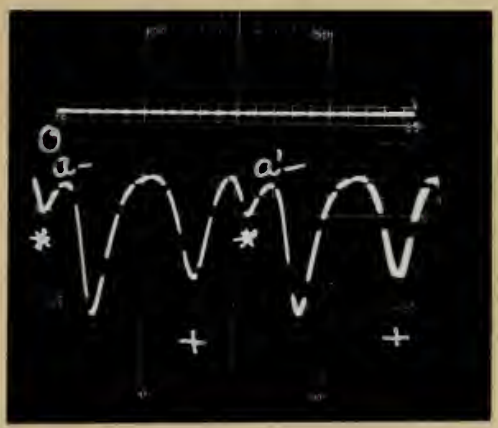


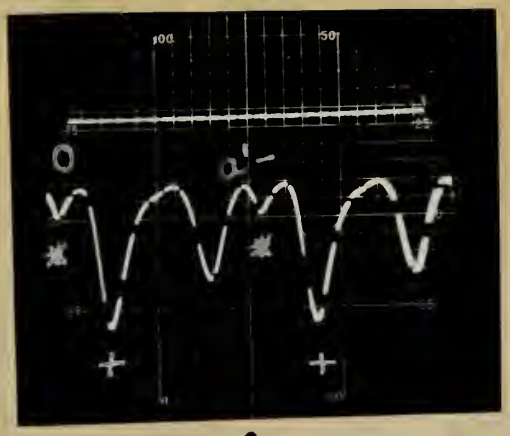
F

FIGURE 19

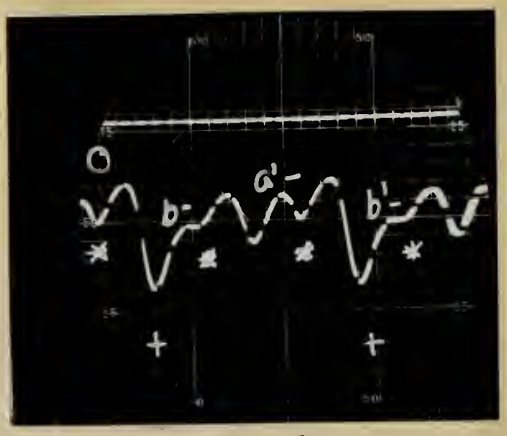
Direction and Velocity of Negative Striation (Plate 1)
61.0ma., 256v., 1507 cps (Mode V)

A: 2.01 cm from cathode
B: 1.87 cm from cathode
C: 1.73 cm from cathode
D: 1.68 cm from cathode
E: 1.62 cm from cathode
F: 1.50 cm from cathode

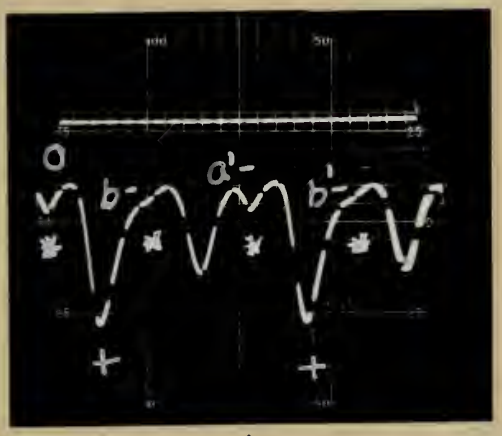
(Maximum intensity is in downward direction from upper zero trace)
(White dot indicates attenuation due to negative striation)



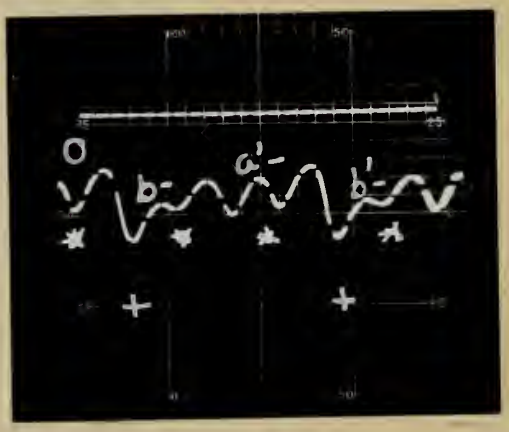
G



J

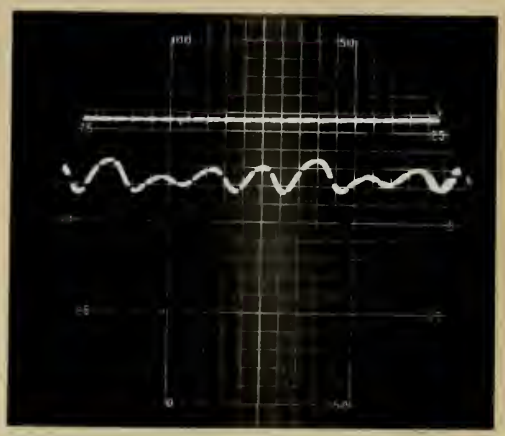


H



K

I



L

FIGURE 20

Direction and Velocity of Negative Striation (Plate 2)
61.0 ma., 256v., 1507 cps (Mode V)

G: 1.44 cm from cathode
H: 1.38 cm from cathode
I: 1.30 cm from cathode
J: 1.13 cm from cathode
K: 1.01 cm from cathode
L: 0.84 cm from cathode

(Maximum intensity is in downward direction from upper zero trace)
(White dot indicates attenuation due to negative striation)

CHAPTER IV

PROBE TECHNIQUE AND PROBE DATA

1. Objective

As stated before, an additional objective of this work was the developing and testing of a method of discharge analysis using probes. It is thought that probes may offer an additional powerful tool for the study of moving striations. From them such time dependent information as plasma potentials, electron temperatures, electron and positive ion concentrations, and electric fields can be obtained for various points in the positive column. Surely, such information will be invaluable in reaching the ultimate understanding of striations.

2. Method of Taking Data

The probe circuit described in Paragraph 8, Chapter II and shown in Fig. 9 was connected. This is a simple arrangement, and it will yield all needed data. The data was taken in the following manner.

First, the tube voltage and current were adjusted to give a stable mode of operation. Then the optical system was focused on the probe to be used, and the light intensity variations at that point were fed into the A side of the oscilloscope. Into the B side was fed the drop across the probe circuit 20,000 ohm resistor. Both sweeps were triggered by the voltage fluctuations across the tube, and thus there was on the scope at all times a

comparison of the time dependent light intensity changes and the probe current fluctuations.

By means of the voltage divider the probe circuit voltage was changed in steps from zero to 180 volts negative with respect to the anode. For each setting of the voltage divider the average d.c. probe current (I_p) and the d.c. voltage output of the divider (E_b) were recorded. Then the B channel of the oscilloscope was calibrated by means of the built-in voltage calibrator in order to determine and record the number of volts represented by the space between 2 horizontal lines on the illuminated grid. When this was completed, a photograph was made using a double exposure method. The first exposure was made of the two zero traces (vertical amplifiers "off") and the illuminated grid taking care to record which trace belonged to the probe. The vertical amplifiers were then turned on and the second exposure was made of the light intensity and probe current traces. Thus, a picture was obtained for each setting of the voltage divider.

After the negatives were developed, they were placed in the photoreader. Then, in order to obtain instantaneous probe currents, measurements were made at specific times along the time scale of the instantaneous voltage drops across the probe circuit resistor since these voltage drops were the means by which probe current was displayed. These measurements were made by counting the number of grid spaces between the zero trace and voltage trace and converting this to volts by means

of the calibration data obtained earlier. Thus, throughout the complete range of voltage divider settings the instantaneous probe currents could be determined for selected times by dividing the voltage drops by the known value of the resistance (R).

Fig. 21 is a sample of the pictures that were obtained. These pictures were taken at probe number 1 which was 32.25 cm from the cathode. The tube current was 48.5 ma; the tube voltage was 264v.

Fig. 21 is further described as follows:

	E_b (volts)	I_p (ma)	Remarks
A	120.0	.0552	Low "O" trace belongs to probe. For this trace 1 vertical grid space = .167v
B	60.0	.0283	Same as for A
C	55.5	.0188	Same as for A
D	52.8	0	Same as for A except 1 vertical grid space = .27v
E	24.5	-1.18	Upper "O" trace belongs to probe. For this trace 1 vertical grid space = 1.7v
F	10.0	-2.41	Same as for E except 1 vertical grid space = 2.5v

The light intensity trace is that one which remains unchanged throughout the series of pictures.

3. Analysis of Data

In Fig. 21A there are shown 5 white dots. Associating the first dot with zero time, the others in turn represent 140, 370, 520, and 660 microseconds. These 5 dots exactly cover one cycle

of the light intensity variation, and it was at these selected times that the probe resistor voltage drop was read in each picture. As already stated these drops were converted to currents (i_s) by dividing by R (20,000 ohms). The voltage drop V_s from probe to anode was obtained next with the relation $E_b = V_s \pm i\,R$.

Using this data there were plotted two curves for each of the selected times. Curve 1 was a probe characteristic curve, i_s versus V_s, and curve 2 was a Langmuir plot, ln i_e versus V_s, where i_e (electron current) = $i_s + i_p$ with i_s and i_p obtained from the probe characteristic curve as shown below in Fig. 22.

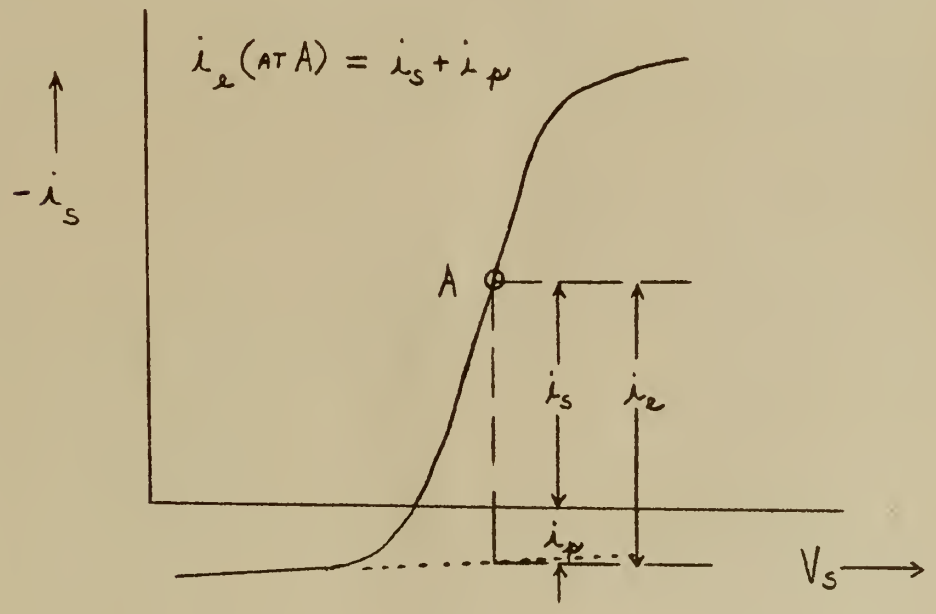


FIGURE 22

Probe Characteristic Curve

The manner of constructing these curves is explained fully in Cobine[3]. Fig. 23 and 24 show these plots for 520 microsec.

The point where the Langmuir plot departs from a straight line represents V_p, the potential of the plasma with respect to the anode. In Fig. 24 V_p = -51.5v.

Using the V_p's obtained for each of the selected times, a curve of V_p versus time was constructed as shown by Fig. 25. Now this curve can be used to construct a curve of electric field deviation (from striation free value) versus time as follows:

Let V_p = potential of plasma with respect to the anode

x = distance along the tube

t = time

v = velocity of the striation

E = electric field deviation from striation free value

then

$$E = -\frac{dV_p}{dx}$$

$$\frac{dV_p}{dx} = \frac{dV_p}{dt}\ \frac{dt}{dx} = \frac{dV_p}{dt}\ \frac{1}{v}$$

$$E = -\frac{dV_p}{dt}\ \frac{1}{v}$$

The velocity of the striation for this particular tube current and voltage (45.8 ma, 264v) was 25 m/sec. Therefore, by computing the slopes at various points along the V_p versus t curve and using the known value of v, it was possible to construct a curve of E versus t as shown in Fig. 26.

Electron temperatures (T_e), electron concentrations (n_{ep}) and positive ion concentration (n_{pp}) were next obtained using

the following relations:

For T_e computation -

$$T_e = \frac{e}{kS}$$

where S slope of straight line portion of Langmuir plot

$e = 1.60 \times 10^{-19}$ coulomb

$k = 1.380 \times 10^{-23}$ joule/°K

For n_{ep} and n_{pp} computation -

$$n_{ep} = n_{pp} = \frac{j_{ep}}{e} \sqrt{\frac{2\pi m_e}{k T_e}}$$

where j_{ep} = random plasma electron current density.

$m_e = 9.11 \times 10^{-31}$ kgm

These computations yielded the below shown results:

time (microsec)	V_p (v)	T_e (°K)	$n_{ep} \equiv n_{pp}$ (per m^3)
0	39.5	16,240	6.18×10^{16}
140	41.85	12,400	6.18×10^{16}
370	43.7	8,200	8.87×10^{16}
520	51.5	12,150	8.97×10^{16}
660	39.5	14,660	6.13×10^{16}

In examining this table it should be emphasized that in so far as light intensity is concerned, 0 and 660 microseconds represent the times of a maximum, 370 microseconds represents the time of a minimum, 140 and 520 microseconds represent the times midway between a maximum and a minimum. The reader should refer back to Fig. 21A remembering that the low points in the light intensity trace are points of maximum intensity. The above table

shows that, under these particular conditions, a maximum in light intensity is accompanied by maximum T_e, and a minimum in light intensity by a minimum T_e. Furthermore, the electron density is rather constant throughout most of the cycle but rises to a maximum at and just following a minimum in light intensity.

We have therefore shown how, for a particular point in the positive column, the time dependent values of V_p, T_e, n_{ep}, n_{pp}, and E can be obtained using probe data. At this point it should be emphasized, however, that to obtain accurate results using the technique described here, the oscilloscope vertical amplifier voltage calibration must be carefully made before each picture is taken. Otherwise the information obtained from the analysis on the photoreader will not be satisfactory. Furthermore, the technique requires a careful selection of the probe current dropping resistor in order that a definite knee can be reached in the Langmuir plot before the probe alters the characteristics of the discharge or takes over the discharge from the anode. The optimum value of this resistance (obtained by a standard load line analysis method) will limit the probe current to a sufficient degree to avoid these dangers and yet at the same time give a well defined knee in the plot.

4. Observations Using Two Probes

In most instances the probe voltage trace displayed on the oscilloscope was of a complex nature. In an attempt to analyze this structure the following procedure was followed.

First, tube current and voltage were set to give a stable mode of operation and then the probe voltage divider was set to give any desired d.c. probe current and probe voltage. Next, several sets of photographs (three pictures per set) were taken. Picture 1 of each set was a photograph of light intensity and probe current fluctuations (measured as voltage drops across fixed probe resistor) at probe 2 (25.75 cm from the cathode). Picture 2 was a photograph of the probe traces at probes 1 and 2 (probe 2 always top trace). Picture 3 was a photograph of the light intensity and probe current fluctuations at probe 1 (32.25 cm from the cathode). The voltage divider was adjusted as necessary when switching from probe 2 to probe 1 so that in each of the pictures the average d.c. current carried by the two probes was the same.

Fig. 27 represents two sets of such pictures as described below:

Set 1 (A,B,C), tube current 14.0 ma, tube voltage 306v, I_p = 0 ma

A - Picture 1, light intensity (top trace) versus current at probe 2

B - Picture 2, current at probe 2 (top trace) versus current at probe 1

C - Picture 3, light intensity (top trace) versus current at probe 1

Set 2 (D,E,F), same conditions as set 1 except I_p=+.02 ma.

Above descriptions for A,B,C in set 1 apply in order to D,E,F. As stated before the light intensity maxima are low points in the light intensity trace; the probe current positive

maxima are high points in the probe trace.

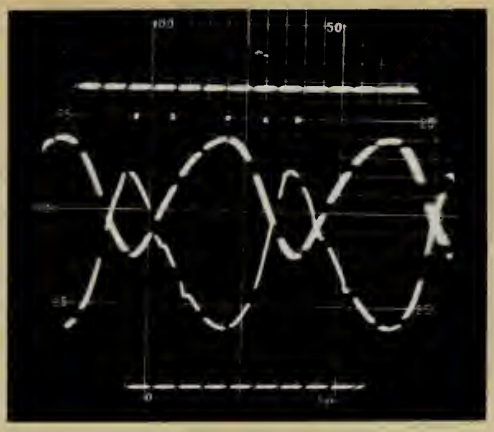
It is interesting to note that the highest positive peaks in probe current are of the same period and are in phase with the light intensity peaks of the positive striation. This is true in pictures 1 and 3 of each set, and since we know that the positive striation is moving with an easily measured velocity, it seems not unreasonable to infer that the positive probe peaks are moving with the same velocity as the positive striation and may be the probe manifestation of positive striation light intensity variation. Furthermore, a careful examination of the two traces in picture 2 of each set reveals a slight displacement of positive peaks in one direction and a similar slight displacement of negative peaks in the opposite direction. This would seem to indicate that these peaks are moving at different velocities, and it may develop that the negative peaks are due to negative striations. A movable probe would be necessary to prove or disprove these suppositions since it would make possible a continuous observation of the peaks throughout the positive column and would thereby provide an accurate means of determining their velocities and directions of motion.

5. Comments

The interesting points which were brought forth in the development of this probe technique have been discussed in paragraphs 2 and 4 above. The testing of the technique involved the analysis of only a very small amount of data, and consequently, no conclusions can possibly be reached on the nature and be-

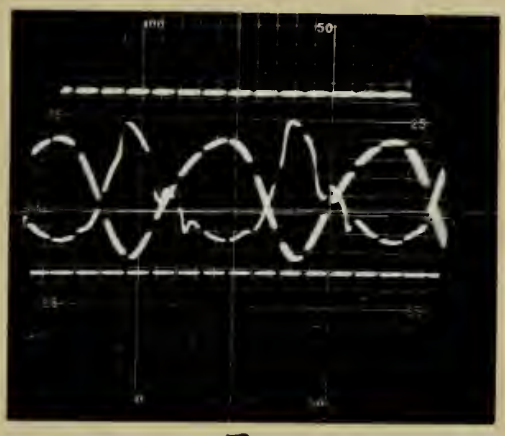
havior of striations based on this fragmentary data alone. It is believed, however, that the objective behind this work with probes has been accomplished. A technique has been developed and tested, and the results appear to be most satisfactory. It should be pointed out that the curves of V_p versus t and E versus t together with calculated electron temperatures agree closely with the results of Pupp[13] although he used two probes rather than one, one of which was moved relative to the other.

Probes should be one of the most direct means of finding out exactly what is taking place in the positive column, and it is the opinion of the writers that this technique along with a movable probe is the best method for future moving striation studies.

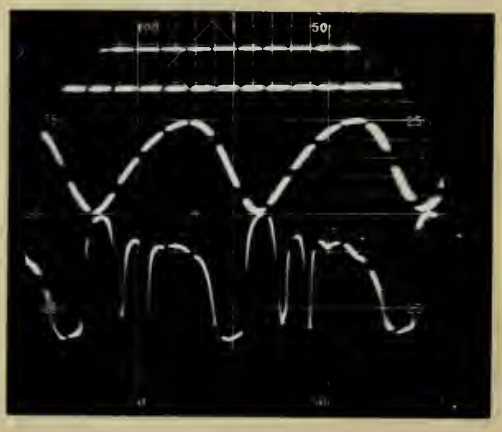


A

D

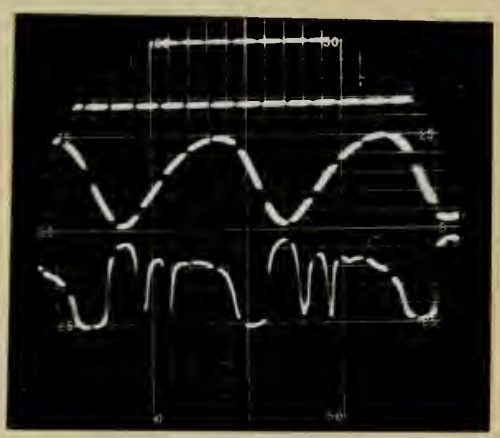


B



E

C



F

FIGURE 21

Probe 1 Current Fluctuations 32.25 cm from Cathode

A. I_p = .0552 ma

B. I_p = .0283 ma

C. I_p = .0188 ma

D. I_p = Oma

E. I_p = 1.18 ma

F. I_p = 2.41 ma

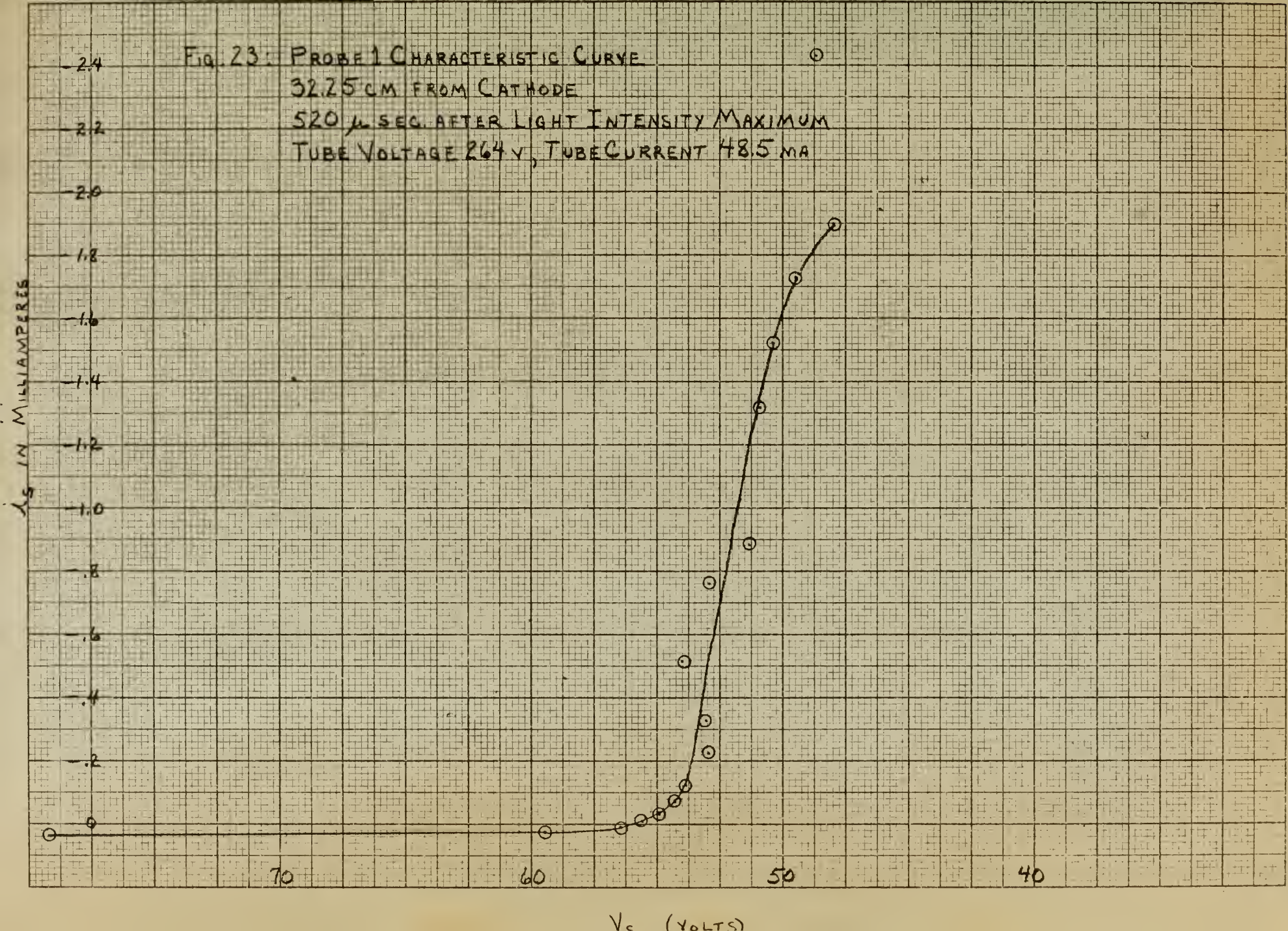


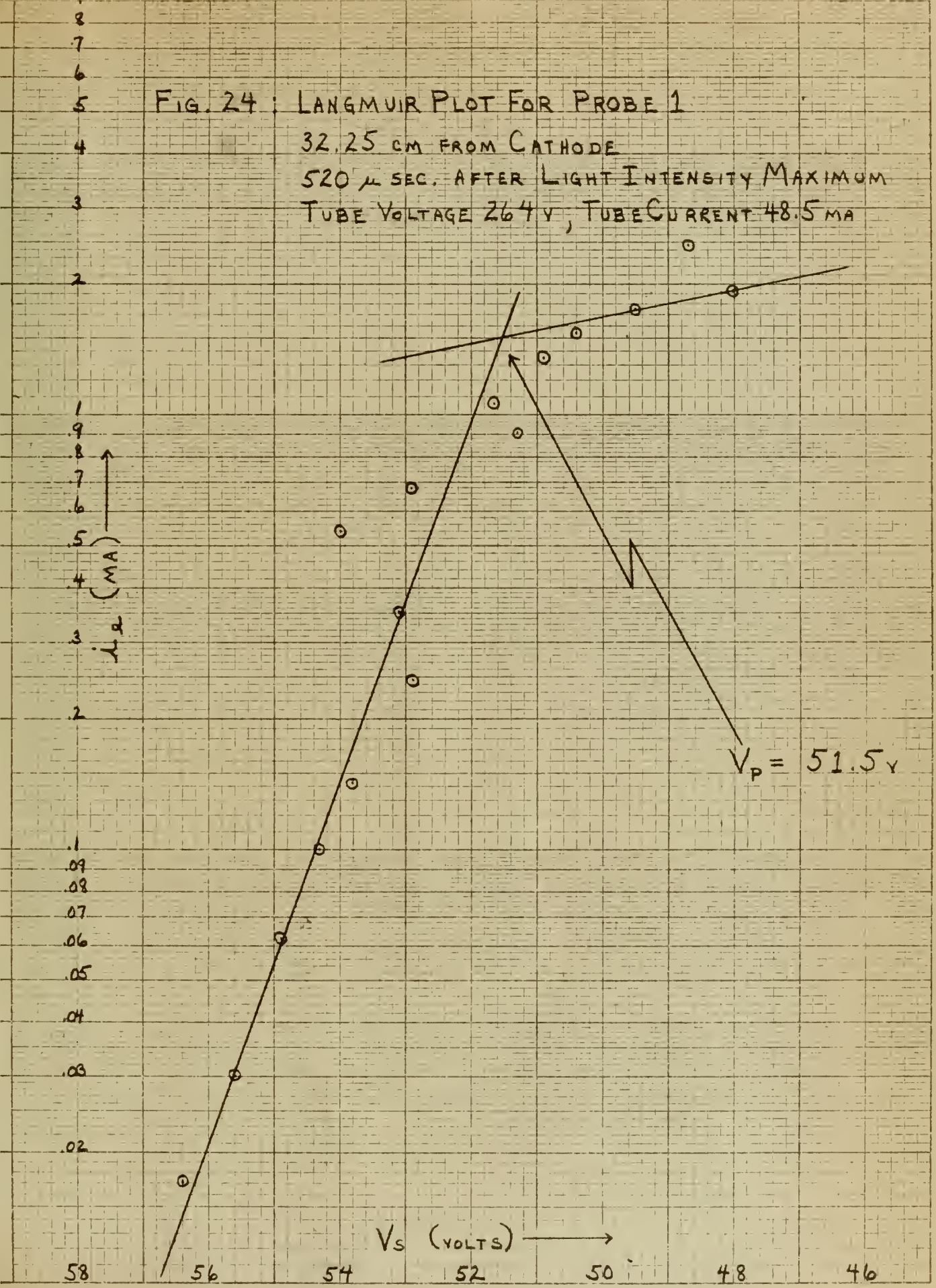
FIG. 23: PROBE 1 CHARACTERISTIC CURVE
32.25 CM FROM CATHODE
520 μ SEC. AFTER LIGHT INTENSITY MAXIMUM
TUBE VOLTAGE 264 V, TUBE CURRENT 48.5 MA
I_s IN MILLIAMPERES
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
.8
.6
.4
.2
0
70
60
50
40
V_s (VOLTS)

FIG. 24 : LANGMUIR PLOT FOR PROBE 1

32.25 CM FROM CATHODE

520 μ SEC. AFTER LIGHT INTENSITY MAXIMUM

TUBE VOLTAGE 264 V, TUBE CURRENT 48.5 MA



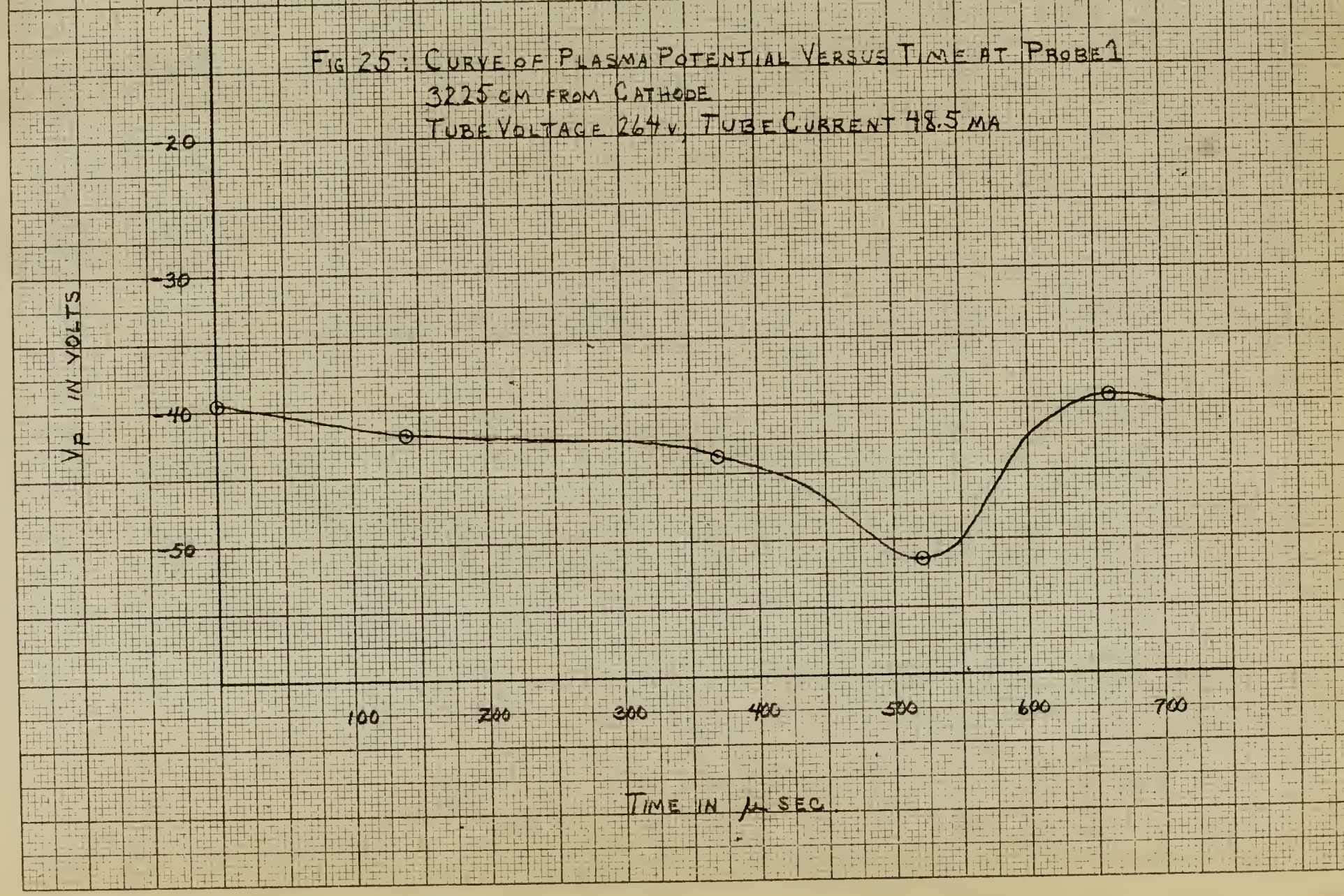


FIG 25 : CURVE OF PLASMA POTENTIAL VERSUS TIME AT PROBE 1
3.225 CM FROM CATHODE
TUBE VOLTAGE 264 V, TUBE CURRENT 48.5 MA

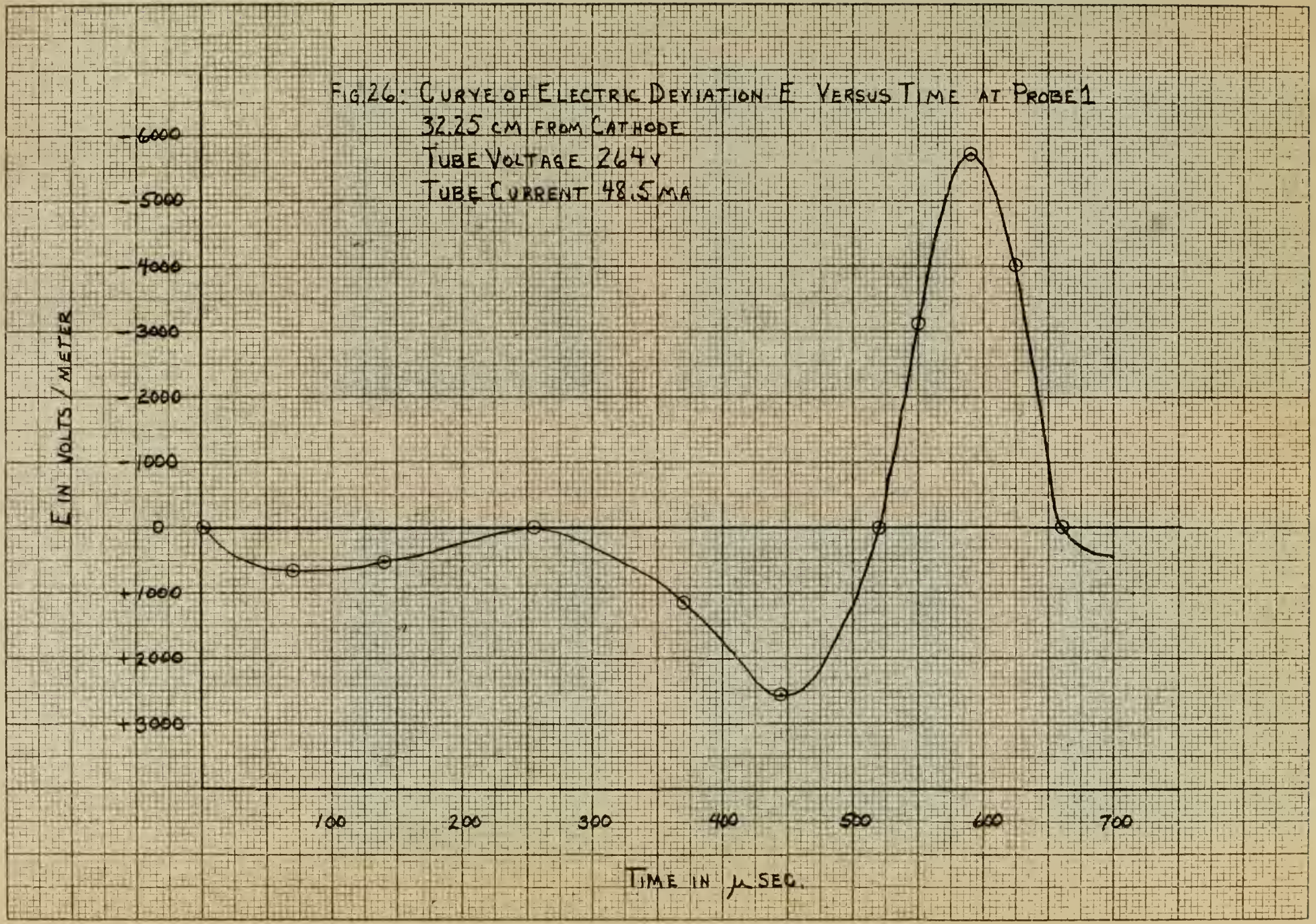
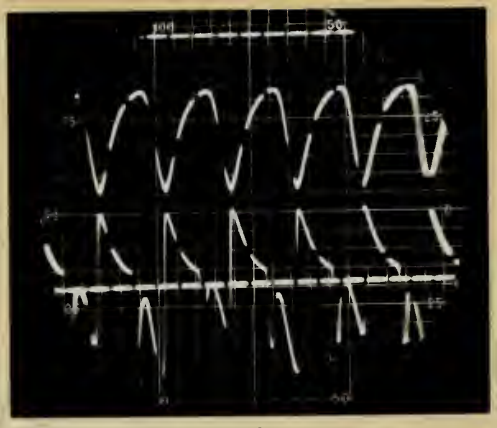
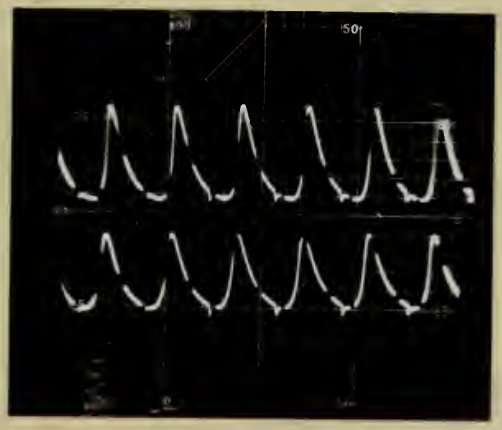


FIG.26: CURVE OF ELECTRIC DEVIATION E VERSUS TIME AT PROBE 1
32.25 CM FROM CATHODE
TUBE VOLTAGE 264 V
TUBE CURRENT 48.5 MA
E IN VOLTS / METER
-6000
-5000
-4000
-3000
-2000
-1000
0
+1000
+2000
+3000
100
200
300
400
500
600
700
TIME IN μ SEC.

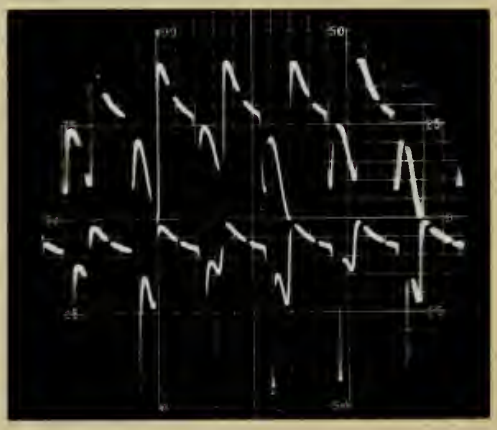
A



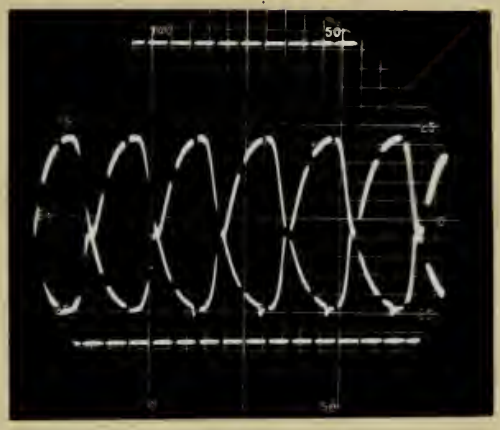
D



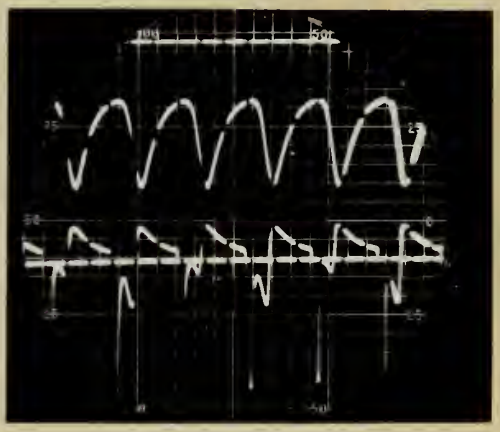
B



E



C



F

FIGURE 27

Probes 1 and 2 - Current and Light Intensity Comparisons
Descriptions on Page 62

CHAPTER V

CONCLUDING REMARKS

1. Discussion of Light Intensity Fluctuations and Comparison with Theory.

Of possible interest and consideration in any theories of the discharge are the following observations:

a. Light intensities did not fall to zero at any time for any position in the discharge glow.

b. There appears to be a phase shift in the discharge as evidenced by current voltage relations at the electrodes.

c. Stable operating conditions may be achieved for most currents at which only one mode of oscillation exists at the given current (neglecting hysteresis). This facilitates observation and analysis.

d. The light intensity waveforms may be regarded as a composite wave composed of the more prominent positive striation component waveform and one or more negative striation component waveforms. The probe studies of Chapter IV, appear to detect the presence of small amplitude negative striations in the plasma. However, since there is no evidence of large amplitude negative striations well into the plasma, one can assume, for this region, that the waveform is essentially that of a positive striation. Near the cathode, large amplitude negative striations appear and the waveform becomes more complex. The direction and

average velocity of a negative striation may be determined by a "time-position" analysis of the "antipeak" it produces by attenuation of the positive striation in the neutralization process.

These observations do not conflict with the Dieke and Donahue Theory of glow discharges as given in Chapter I. They do raise some questions which should be further investigated. Several areas and methods for such investigations have been suggested in this paper. Additionally, many other mathematical and experimental methods have been reported by other workers:

a. Effects of magnetic and electric fields[10,17].

b. Stroboscopic techniques[17].

c. Study of high frequency discharges[8].

d. Using an a.c. generator to create artificial striations[17].

e. Employing a mass spectrograph in a hollow probe[10].

f. Analysis by principles of kinetic theory[14].

2. Comments on the Probe Study.

It is considered that a quite satisfactory probe technique has been developed in this work. Two points, which have been discussed in Chapter IV, should be reemphasized in the application of the technique.

a. The probe circuit dropping resistor must be of proper size.

b. The voltage calibration of the oscilloscope must be done with care.

Although, in the test of the technique, only five points

were used to cover a light intensity fluctuation cycle, it was seen that the technique yielded results which agreed closely with the previous work of Pupp[13]. There is every reason to believe that this probe technique can be used without difficulty in future studies.

Comparison of current traces at two probes has shown that there is a possiblity that the negative peaks in the traces may be due to negative striations. This emphasizes the need for a movable probe study to get the velocity and direction of motion of these negative peaks.

3. Recommendations for further Work

Much remains to be done in gathering and interpreting data before a theory of the striations can be established with any degree of certainty. Investigations which are considered to be of primary importance are listed below.

a. A spectroscopic study of the glow discharge with emphasis on establishing the striation movement mechanism.

b. A movable probe or movable electrode study with emphasis on establishing electric fields, electron and positive ion concentrations, and electron temperatures, all as a function of time, at many points in the positive column.

c. Studies at other pressures and with other gases with emphasis on correlating patterns of behavior.

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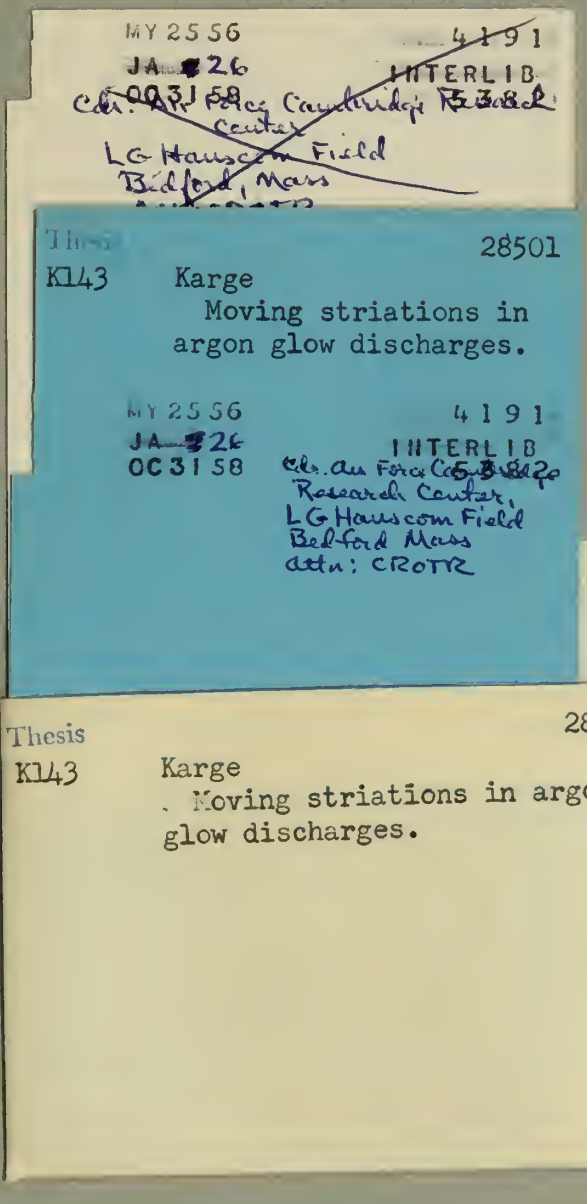
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